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NOAA Technical Report NOS CO-OPS 084

Casco Bay, Maine Current Survey 2014

Portland Head Lighthouse, Maine. Photo Credit: Katerina Glebushko, NOAA

Silver Spring, Maryland

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U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) provides the National infrastructure, science, and technical expertise to collect and distribute observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and tidal current products required to support NOS' Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), a national network of Physical Oceanographic Real-Time Systems (PORTS®) in major U. S. harbors, and the National Current Observation Program consisting of current surveys in near shore and coastal areas utilizing bottom mounted platforms, subsurface buoys, horizontal sensors and quick response real time buoys. The Center: establishes standards for the collection and processing of water level and current data; collects and documents user requirements, which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

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Casco Bay, Maine Current Survey 2014

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March 2017

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EXECUTIVE SUMMARY

In 2014, the National Ocean Service's Center for Operational Oceanographic Products and Services conducted a circulation survey of the Casco Bay region of Maine, including the Kennebec River. This survey's main goals were to update or create tidal current predictions and support hydrodynamic model development. This survey yielded quality data at 22 locations, including a new reference station at Portland Harbor Entrance.

Currents were observed by mounting acoustic Doppler current profilers (ADCP) into either bottom mounts or subsurface taut-line moorings at predetermined stations. The ADCPs were programmed to internally record 6-minute data ensembles for at least one lunar month. In addition to profile data on each location's current speed and direction at discrete depth bins, each ADCP provided data on water temperature, sensor depth, pitch, roll, heading, and quality control measurements. Additionally, a conductivity, temperature, and depth cast was taken at each station during deployment and recovery operations.

All ADCP data collected were analyzed for quality and to separate the harmonic frequencies of the tidal signal from the residual or nontidal flow.

Overall, 19 stations had data of sufficient quality and length to be used to update National Oceanic and Atmospheric Administration products. Results from three stations are presented, including Portland Harbor Entrance, which has been designated as a reference station in the Tidal Current Tables. In general, tidal currents observed during this study were: 1) dominated by the M_2 tidal constituent and 2) influenced by local bathymetric constrictions, which limited flow to be predominantly oriented along the channel (major axis), creating extremely rectilinear flow fields.

1. INTRODUCTION

The National Ocean Service's (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) manages the National Current Observation Program (NCOP). The program's goal is to improve the quality and accuracy of the National Oceanic and Atmospheric Administration (NOAA) Tidal Current Tables (NOAA, 2014), which are published annually as required by 33CFR§164.33. Improving this information is a critical part of NOS' efforts toward promoting safe navigation in our Nation's waterways. CO-OPS, under the authority of *33USC§883a-b*, acquires, archives, and disseminates information on tides and tidal currents in U.S. ports and estuaries, a vital NOS function since the 1840s. Mariners require accurate and dependable information on the movement of the waters in which they navigate. Ships continue to grow in length, width, and draft and as seagoing commerce continues to increase there is an increased risk to safe navigation in the Nation's ports (Office of Coast Survey, 2012).

The flow dynamics of an estuary or tidal river can be modified by changes in natural factors or through man-made alterations such as the dredging of channels, harbor construction, bridge construction, the deposition of dredge materials, and the diversion of river flow. Changes in water flow and tidal dynamics can occur rapidly or over several decades and may affect the accuracy of tide and tidal current predictions. New data must be collected periodically to assure that predictions are reliable and to adjust them accordingly.

CO-OPS has developed expertise in deploying current profilers throughout the Nation's coastal waters via the NCOP program. Data collected through this program are utilized in the production and refinement of products by NOAA and the user community, such as the validation of hydrodynamic forecast systems, updating existing tidal current predictions, and the establishment of new tidal current prediction locations. These products are used to ensure safe navigation, make informed coastal zone management decisions, and protection life and property.

The data described in this report were collected by NCOP during a survey in 2014. A total of twenty-five stations were occupied for a period of at least one lunar month. Of the 25 stations, 22 produced data of sufficient quality to perform harmonic analysis and generate tidal current predictions. Data collected for the 22 successful stations contain vertical current profiles (speed and direction), water temperature, pressure, and additional quality control variables. The collected data were analyzed and reports were generated detailing statistical and harmonic analyses to assure high quality tidal current predictions. All data and analysis reports presented herein are available by contacting co-ops.userservices@noaa.gov.

2. PROJECT DESCRIPTION

With previous surveys dating to the 1940s and 1970s, Casco Bay (CAB) was identified by internal assessments within CO-OPS as a high-priority current observation project for NCOP utilizing modern acoustic Doppler current profilers (ADCPs). Site locations were proposed based upon meetings with users, NOAA experts, professional mariners, and academia and were finalized based on oceanographic needs and by criteria set forth by the International Hydrographic Organization (IHO S-44 §4.5). Furthermore, a hydrodynamic model being developed by NOS (Gulf of Maine Operational Forecast System or GoMOFS) will benefit from this observational data when conducting their hindcast skill assessment.

In 2011, a reconnaissance was conducted where proposed sites were visited to gather their physical characteristics, which were used for configuring a station for occupation. During reconnaissance operations, each site was visited using a vessel equipped with: a fathometer to determine the depth of the site; a conductivity, temperature and depth (CTD) sensor to determine salinity and density; and a Ponar-style bottom sampler to determine the nature of the seabed at the site (e.g., mud, silt, sand). Based upon the reconnaissance, 25 current measurement stations were identified and, during the summer of 2014, occupied using methods described in section 3. This technical report focuses on the results of these current meter deployments.

2.1 Geographic Scope

Tidal current measurements were collected from the northernmost station in the Kennebec River at Richmond, Maine to the southernmost station at the entrance to the Saco River, with a cluster near Portland, the 44th largest port in the U.S. by tonnage (U.S. Army Corps of Engineers, 2015). The map (Figure 1) shows the deployment locations of all stations followed by a station listing (Table 1).

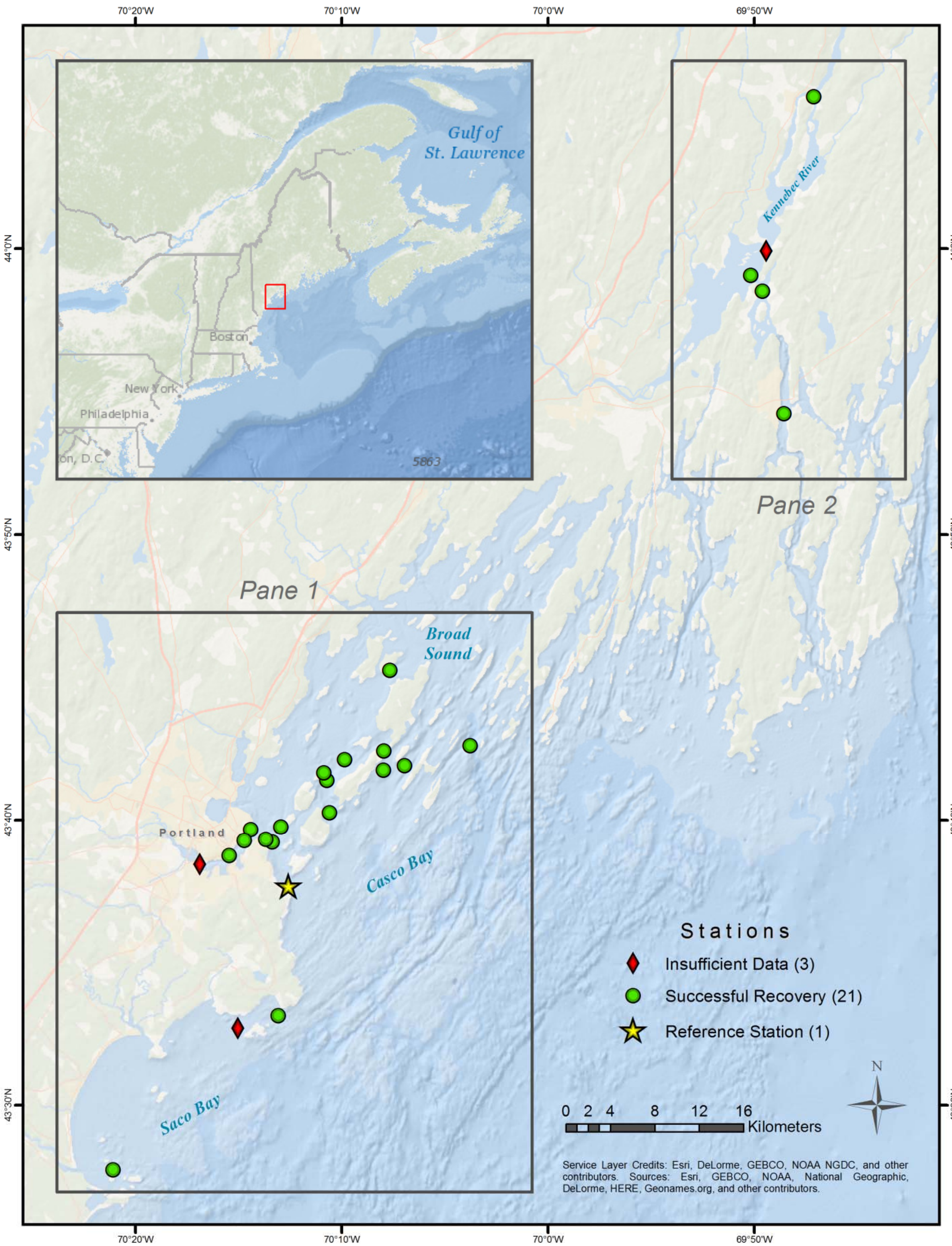

Figure 1. Map of project area.

Table 1. Station list with position (+ is north and east, - is south and west), depth as recorded at deployment and station occupation start and end dates.

Station ID	Name	Latitude	Longitude	Depth (m)	Start	End
CAB1401	Portland Harbor Entrance	43.6280	-70.2095	17.7	5/10/2014	7/30/2014
CAB1402	Spring Point, NE of	43.6537	-70.2227	16.3	5/10/2014	6/16/2014
CAB1403	Portland Breakwater Light, 0.3 M east of	43.6553	-70.2278	18.3	5/10/2014	6/17/2014
CAB1404	Diamond Island Roads	43.6625	-70.2157	14.7	6/17/2014	7/30/2014
CAB1405	Ocean Gate Terminal	43.6610	-70.2400	7.1	6/17/2014	7/30/2014
CAB1406	State Pier, Portland Harbor	43.6547	-70.2450	11.8	6/18/2014	7/30/2014
CAB1407	Fore River, Portland River Bridge	43.6458	-70.2573	13.0	5/10/2014	6/17/2014
CAB1408	Veterans Memorial Bridge, S of	43.6405	-70.2810	7.0	6/19/2014	7/31/2014
CAB1409	Chandler Cove, S. Ent	43.7070	-70.1323	16.0	6/19/2014	7/31/2014
CAB1410	Hussey Sound, Between Long & Peaks Island	43.6708	-70.1763	32.0	6/19/2014	7/31/2014
CAB1411	Long Island, Mariner Ledge	43.7020	-70.1642	15.3	5/11/2014	6/17/2014
CAB1412	Hussey Sound, Cow Island	43.6898	-70.1783	27.8	5/11/2014	6/17/2014
CAB1413	Cow Island, NE of	43.6942	-70.1810	19.5	6/17/2014	7/31/2014
CAB1414	Lucksee Sound Between Hope and Cliff Is.	43.6984	-70.1157	21.4	6/19/2014	7/31/2014
CAB1415	Stepping Stones	43.6958	-70.1327	17.4	5/11/2014	6/17/2014
CAB1416	Eagle Island W. of., Broad Sound	43.7100	-70.0628	41.0	5/11/2014	6/17/2014
CAB1417	Littlejohn Island, South of Town Ledge	43.7542	-70.1277	16.5	5/11/2014	6/17/2014
CAB1418	Maine Kennebec Bridge, 0.2 M SW of	44.0880	-69.7852	7.6	6/27/2014	8/1/2014
CAB1419	Goose Cove, south of Chops Passage, Kennebec River	43.9752	-69.8267	15.2	6/20/2014	8/2/2014
CAB1420	Bath Iron Works, Kennebec River	43.9038	-69.8093	14.0	6/20/2014	8/1/2014
CAB1421	Merrymeeting Bay, north of Chops Passage, Kennebec River	43.9843	-69.8362	15.5	6/20/2014	7/31/2014
CAB1422	Lillys Cove	43.9983	-69.8236	13.1	6/20/2014	8/2/2014
CAB1423	Seal Cove, Cape Elizabeth	43.5523	-70.2177	10.7	5/17/2014	6/16/2014
CAB1424	Richmond Island Harbor	43.5446	-70.2503	15.8	5/17/2014	6/16/2014
CAB1425	Saco River Entrance	43.4621	-70.3512	9.9	5/12/2014	6/16/2014

3. METHODS

3.1 Description of instrumentation and platforms

On-water operations were conducted on the R/V Jamie Hanna (Figure 2) under contract to NOAA. Currents were measured with an ADCP moored in place with a suitable mounting configuration determined by weighing factors such as station depth, seafloor composition, expected maritime activities, anticipated currents, and available inventory. The three stations (CAB1408, CAB1422, and CAB1424) that did not produce sufficient quality data will not be described further in this report. All 22 remaining stations used Teledyne RD Instruments (TRDI) Workhorse Sentinels with frequencies of 300, 600 or 1200 kilohertz (kHz). The instrument frequency was determined primarily by anticipated depth below the surface at mean higher high Water (MHHW) plus an added buffer to account for uncertainties in depth and significant events (Table 2).

Table 2. Workhorse Sentinel NCOP approximate range by frequency.

Low range (m)	High range (m)	Frequency (kHz)
0.5	15	1200
10	40	600
25	110	300

At each station, the ADCP was mounted in either a subsurface taut-line moored buoy or one of three types of bottom-mounted platform configurations. The specifics of the bottom mounts used are described in Table 3. All platforms were positioned on the seafloor with no surface presence and were recovered by enabling an acoustic release. In the event the acoustic release failed to work properly, a secondary means of recovery was used.

Figure 2. Back deck of the R/V Jamie Hannah in Portland Harbor, with platforms prepared for deployment.

3.2 SUBS

The taut-line mooring systems are comprised of a model A2 Streamlined Underwater Buoyancy System (SUBS) floatation unit manufactured by Open Seas Instrumentation, Inc., two Edgetech acoustic releases (typically the Coastal Acoustic Release Transponder [CART] model) in a tandem configuration, a precast concrete anchor clump, and related hardware. For this report, the term SUBS may refer to both the buoy and entire mooring system (Figure 3). The ADCP is held in the SUBS A2 buoy unit by a modified bucket and stainless steel arm assembly. The name A2 denotes that the ADCP is held in the buoy unit and the unit contains two floatation balls. CO-OPS typically fills voids in the A2 unit with foam to mitigate loss of buoyancy due to sedimentation.

While deployed, the concrete anchor rests on the seafloor, and the SUBS points into the current with the ADCP facing upward, collecting data vertically through the water column.

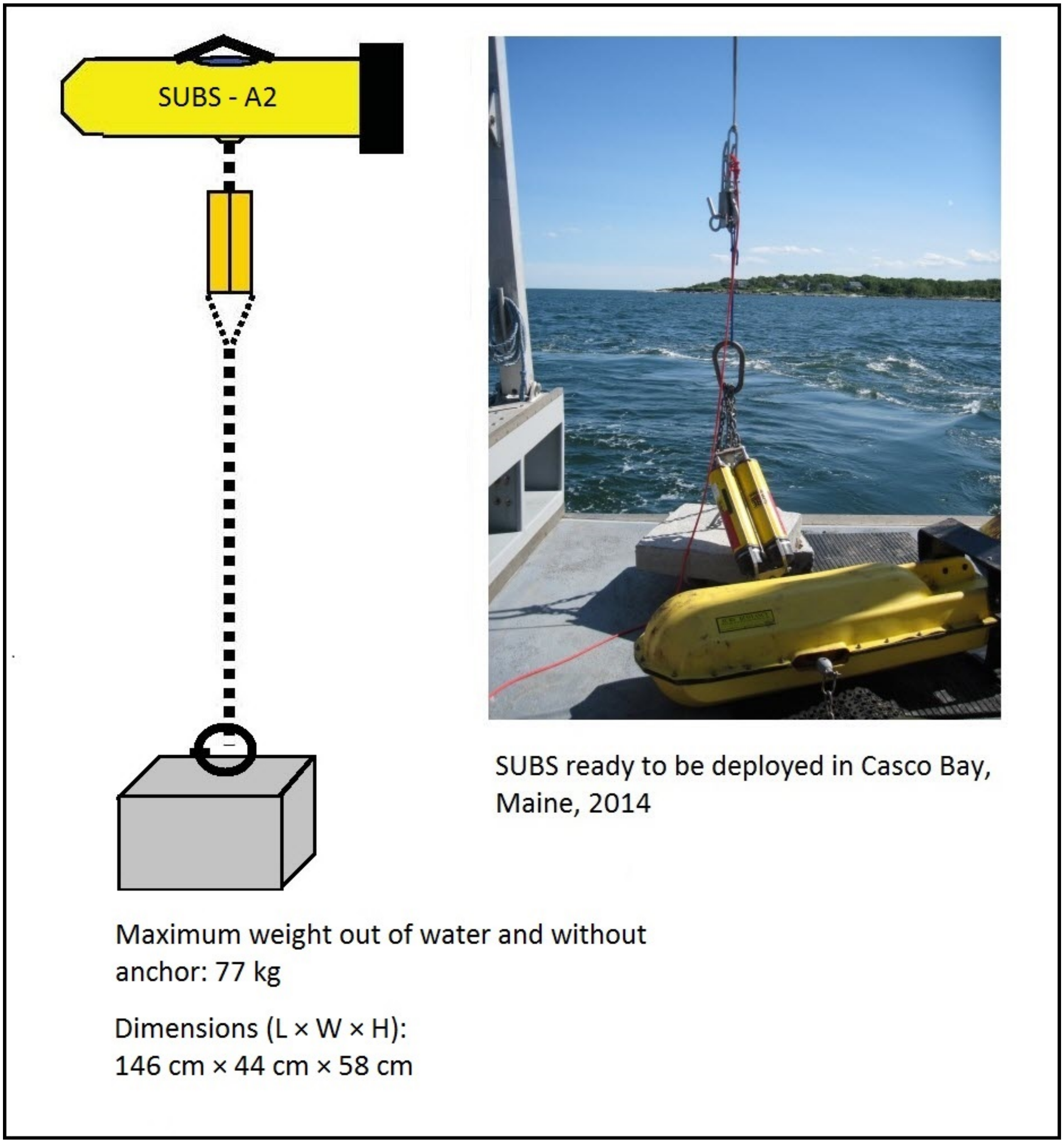

Figure 3. Schematic and images of a taut-line mooring SUBS.

3.3 Bottom mounts

Bottom mounts are designed to rest on the seafloor and provide a stable platform for an upward-facing ADCP during station occupation. Three bottom-mount platform configurations were used during this project: The first is a CO-OPS-designed and contract-built ES-2 (named for the platform designer Eddie Shih); second is a Trawl-Resistant Bottom Mount (TRBM), manufactured by Flotation Technologies (now DeepWater Buoyancy); and third, a miniaturized-TRBM (MTRBM) manufactured by Mooring Systems Inc. Table 3 provides general specifications and deployment and recovery methods for each of the platforms.

Table 3. Bottom mount platforms.

Platform	**Specifications empty (in inches).**	**Deployment and recovery**	**Picture of platform**
ES-2	88 × 70 × 33 800 lb in air	Lowered to the bottom. Acoustically released pop-up buoy to the surface. Entire platform is pulled from bottom.	
TRBM	73 × 70 × 20 1000 lb in air 240 lb in water Float buoyancy 200 lb	Free-fall from surface. Syntactic foam pod holding ADCP is released acoustically and recovered on the surface. Aluminum base is then recovered using line between pod and base.	
MTRBM	70 × 48 × 19 132 lb in air 50 lb in water	Lowered to the bottom. Acoustically released float ball to the surface. Entire platform is pulled from bottom.	 Standard MTRBM system manufactured by MSI

Table 4. Instrument and platform configurations.

Station ID	Depth (m)	Freq. kHz	Pings	Bins Collected	Bin Size (m)	Mount Type
CAB1401	17.7	600	90	20	1	TRBM
CAB1402	16.3	1200	90	15	1	ES-2
CAB1403	18.3	600	90	25	1	ES-2
CAB1404	14.7	600	90	20	1	ES-2
CAB1405	7.1	1200	90	30	0.5	MTRBM
CAB1406	11.8	600	90	25	1	ES-2
CAB1407	13.0	600	90	20	1	ES-2
CAB1409	16.0	600	90	25	1	MTRBM
CAB1410	32.0	300	60	20	2	SUBS
CAB1411	15.3	600	90	20	2	MTRBM
CAB1412	27.8	300	60	15	2	SUBS
CAB1413	19.5	300	60	15	2	TRBM
CAB1414	21.4	300	60	15	2	SUBS
CAB1415	17.4	600	90	20	1	MTRBM
CAB1416	41.0	300	60	20	2	SUBS
CAB1417	16.5	600	90	20	1	MTRBM
CAB1418	7.6	1200	90	25	0.5	MTRBM
CAB1419	15.2	600	90	20	1	TRBM
CAB1420	14.0	1200	90	20	1	ES-2
CAB1421	15.5	600	90	25	1	MTRBM
CAB1423	10.7	1200	90	15	1	TRBM
CAB1425	9.9	1200	90	30	0.5	TRBM

3.4 Data collection

Each ADCP was configured to collect data in 6-minute increments with averaged ensembles of acoustic pulses (pings). The number of 'pings per ensemble' was determined using TRDI's *PlanADCP* software, accounting for the anticipated duration of the deployment and the physical characteristics of the station. Teledyne RD Instruments' Workhorse Sentinels are self-contained ADCPs with internal data storage and battery packs. For this project, stations were configured to leave enough battery life to allow the instrument to be used for two deployment cycles. This negated the need to switch batteries and perform new compass calibrations, thus minimizing the time required to recover a unit and redeploy it in another location.

Unlike single-point current meters, ADCPs may be configured to partition the water column into discrete depth bins based on the time it takes for a ping to be sent and a portion of it to return. These bins are configured by weighing higher resolution (smaller bins) with lower standard deviation (larger bins) while accounting for a portion of the water column near the water surface, which will be lost to sidelobe interference (approximately 6%) and blanking distance from the ADCP head. Blanking distance varies as a function of ADCP frequency and accounts for the time it takes for the ceramics in the transducer to be quiet enough for them to receive the ping's return.

Default settings for TRDI Workhorse were used: 44 centimeters (cm) for 1200 kHz; 88 cm for 600 kHz; and 176 cm for 300 kHz. For each station, the configuration settings, including pings per ensemble, number of bins, bin size, estimated salinity, and planned depth are saved in *PlanADCP*.

ADCPs compute water velocity by measuring each acoustic ping's return signal for Doppler shift. A profile is the relationship of currents within bins to each other, through the water column. Bin 1 is always the deepest bin measured when ADCPs are used in an upward orientation on the seafloor. During these deployments 0.5 meter (m) to 2 (m) (approx. 1.6 feet [ft] to 6.6 ft) deep bins were used (Table 4). The following ancillary measurements were collected and used as data quality assurance parameters: water temperature and pressure (depth) collected at the sensor's head, instrument tilt and orientation, and beam echo and correlation magnitude for each of the four separate transducers at each depth bin of the water column. Values for orientation (heading, pitch, and roll) as well as acoustically derived values (echo amplitude and correlation magnitude) were also provided by the ADCP.

ADCPs were calibrated and tested for proper operation using built-in internal testing algorithms. Upon completion of these procedures, a unique configuration file was uploaded to each instrument based upon settings derived from *PlanADCP*. A unique five-character deployment name and a time to start pinging were also programmed. If the instrument was reused, a reexamination of the ADCP's performance was conducted, and a setup file was uploaded based upon new configuration settings for the new location. Instruments were not recalibrated as the battery packs were not changed.

Concurrent with each deployment and recovery, a CTD profile was taken using a YSI Castaway CTD to ascertain those physical properties of the seawater at the approximate location of each station.

Currents were analyzed for tidal constituents, and a new reference station was established at Portland Harbor Entrance. Predictions were made available online via the NOAA Currents Web interface and updates were published beginning in the 2016 Tidal Current Tables. These data may also be used to improve and validate the GoMOFS.

3.5 Description of data processing and quality control

The sampling rate for the ADCP data was 10 per hour (centered every 6 minutes from the top of the hour through 54 minutes past the hour). Each sample was an average of evenly timed pings ranging from 60 for the 300 kHz ADCP to 90 for both the 600 kHz and 1200 kHz ADCPs. Even though the fastest tidal period is about 2 hours, 6-minute samples enable a high-resolution measurement of the maximum and minimum tidal currents and the ability to capture short duration nontidal events. This rate also provides a statistically sound time series in which erroneous records are less likely to influence the longer series.

All ADCP data collected were analyzed to separate the harmonic frequencies of the signal from the residual or nontidal flow (Parker, 2007). Data were extracted from the binary instrument output into columnar ASCII data and then were further processed by NOAA's harmonic analysis routines (Zervas, 1999). Harmonic analyses were performed upon the time, speed, and direction data of the time series. Other parameters of the time series record (e.g., echo amplitude, tilt, and error velocity) provide an indication of the quality of the data at each time-step.

Quality control measures were implemented to mark each record as bad, good, or questionable (Paternostro, Pruessner, & Semkiw, 2005); (Cothran, 2006). Questionable data were reviewed by an experienced analyst and marked as either bad or good. Only good data were disseminated to the public or used for harmonic analysis. Quality control measures consisted of boundary threshold checks for speed, tilt (pitch and roll), echo amplitude, correlation magnitude, and rate of change checks for speed, pitch, roll, and heading. An automated algorithm flagged the records that failed any of these thresholds.

A principal component analysis was performed on the current velocity time series to determine the major axis of flow. This calculation enables a transformation from *uv* current velocity to major and minor axes (generally along- and cross-channel respectively). Representing the currents in the major and minor axes components is especially beneficial in coastal and estuarine areas (like Casco Bay) since often a significant majority of energy is along the major axis. In these cases, we can effectively represent the tidal currents with a single variable (major axis current speed).

The preferred harmonic analysis method is the mathematical optimization technique of least squares. The least squares calculation allows for the presence of gaps of missing or poor-quality data and functions on a time series of any length. Using this method, all tidal constituents were solved for explicitly and then subtracted from the original signal. A residual signal was left, which was in turn optimized again for the next largest constituent. This process continued until a low threshold was reached or all the required constituents were solved. The least squares method was used to calculate harmonic constituents at all Casco Bay stations.

Once the original time series is decomposed into its harmonic tidal constituents, a new series can be reconstructed to give the tidal component of the current during a time in the past, present, or future. Predictions are possible because each constituent has a known frequency, and the amplitude and phase are determined via the harmonic analysis. The prediction of the astronomical forces can be produced by the summation of the individual constituents' sine waves. (Parker, 2007)

Daily-predicted tidal currents are published by NOAA every year for select stations in Table 1 of the Tidal Current Tables. Stations listed in this section are considered reference stations. They were selected for navigational significance due to geographic location, heavy traffic, hazardous locations, strong currents or a combination of these factors.

Subordinate stations are listed in Table 2 of the Tidal Current Tables. These stations list average timing and speed ratio offsets from a designated reference station (located in Table 1 of the Tidal Current Tables) at each of the four phases of the tidal current (slack before ebb [SBE], maximum ebb, slack before flood [SBF], maximum flood). The time offset from a reference station to a subordinate was calculated using the Greenwich Interval (GI), which is the mean time interval from the moon passing over the Prime Meridian to each phase of the tidal current at a station location. Predictions provided online by CO-OPS are generated directly from harmonic constituents, thereby eliminating the reference/subordinate relationship.

4. PHYSICAL OCEANOGRAPHIC OVERVIEW OF THE REGION

4.1 Region Overview of Tides and Tidal Currents

Casco Bay is a tidally dominant embayment located on the western side of the Gulf of Maine characterized by a mostly rocky, ragged shoreline. It lies between Cape Small and Cape Elizabeth and is the northernmost portion of Bigelow Bight, which continues south to Cape Ann, Massachusetts. Along Casco Bay's southwestern corner lies Portland, which is Maine's largest city and port. Tides within the region are semidiurnal and meso-tidal (tidal range of 2–4 m or about 6.5–13 ft) (Figure 4). NOAA has been observing tides at Portland (station 8418150) since 1910, and presently has a published mean tide range (MN) of 2.781 m (9.124 ft), and a great diurnal tide (GT) range of 3.019 m (9.905 ft) (Figure 5). Observed currents within Casco Bay are almost entirely semidiurnal and tidal.

Based upon CTD observations taken during deployment and recovery, salinity was well-mixed and consistent for stations in Casco Bay, (Figure 6), with near-surface and depth measurements within 2 practical salinity units of each other.

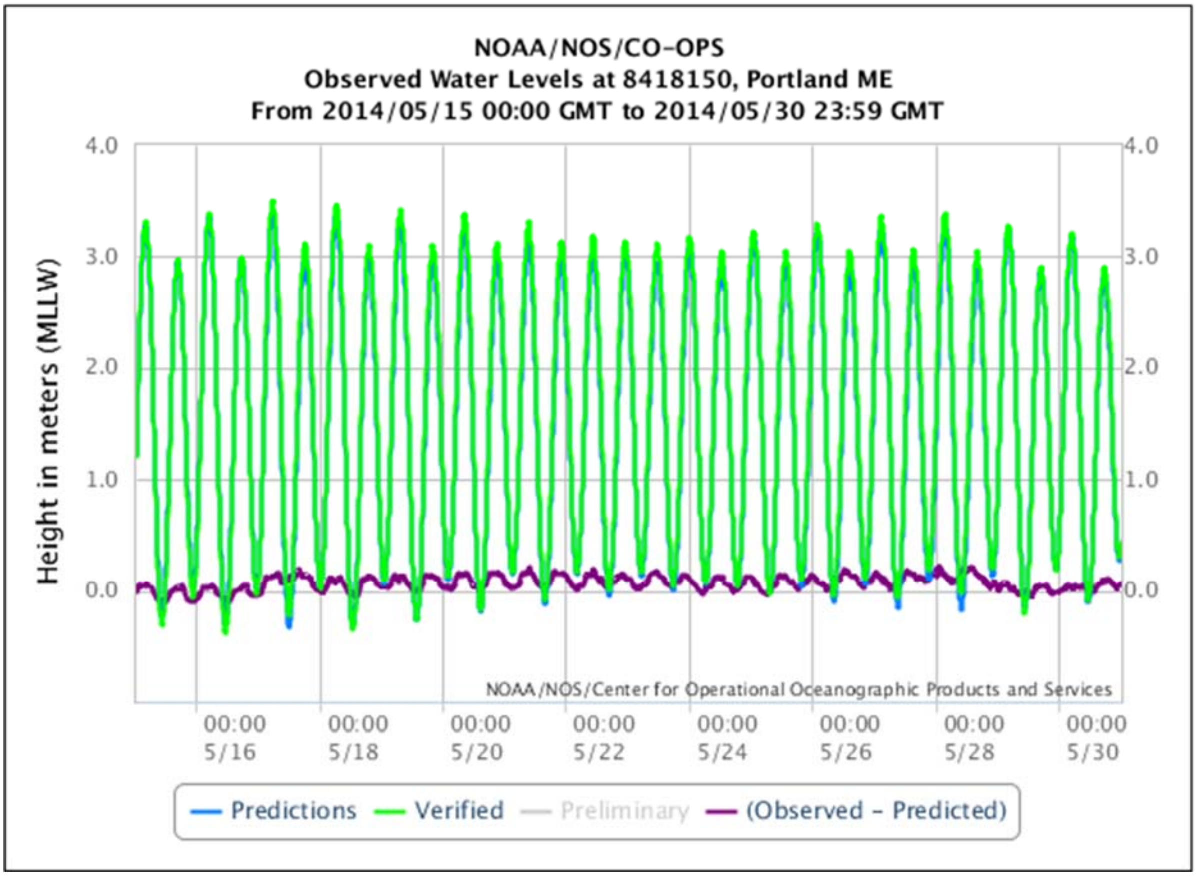

Figure 4. Water level observation at 8418150, Portland, Maine from March 15–30 2014. Residual water level elevations are shown in purple.

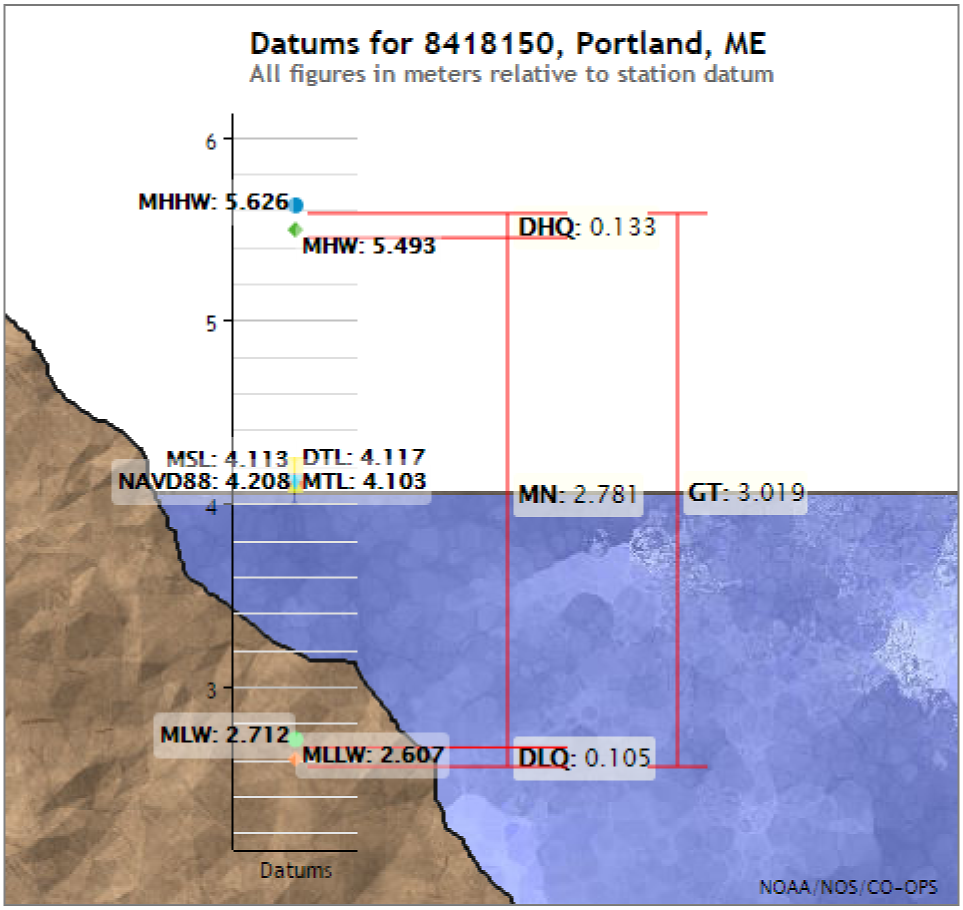

Figure 5. Tidal datums for Portland, Maine (1983–2001 Epoch).

It should be noted, that neither the stations in the Kennebec River nor the two southernmost stations are within Casco Bay. Bath, Maine (8417227) on the Kennebec River has published tidal ranges of 2.085 m (6.840 ft) (MN) and 2.261 m (7.420 ft) (GT). The Kennebec River was almost entirely fresh at all stations sampled. Observed currents in the Kennebec River were extremely tidal, with the tidal component accounting for over 90% of the current energy at all stations, including 99% at two of the stations (CAB1419 and CAB1420).

Salinity values were similar to Casco for the two coastal stations outside of the Bay (CAB1423 and CAB1425); however, salinity at CAB1425 may fluctuate widely during freshwater runoff (freshet) events due to its proximity to the Saco River which has a catchment of approximately 1771 square miles (mi^2) (4587 km^2) (National Ocean Service, 1985). Camp Ellis, Saco River (8418606) has published tidal ranges of 2.719 m (8.920 ft) (MN) and 2.952 m (9.690 ft) (GT). Currents at the two southern stations were somewhat less tidal than those in Casco Bay, with tidal currents at CAB1423 only accounting for about half of the observed energy.

It should also be noted that these observations were conducted during a relatively short window during the late spring to mid-summer. Seasonal and inter-annual variation will not be observed on these time-scales. Furthermore, stations in or near rivers may show significant deviation from predictions during freshets. Table 5 provides rainfall totals at Portland during the period of observations.

Table 5. 2014 precipitation, in inches, at the Portland Jetport during project **(National Weather Service, 2014)**.

Month (2014)	Rainfall	Normal	Departure
May	3.87	4.01	-0.14
June	4.30	3.79	+0.51
July	6.12	3.61	+2.51

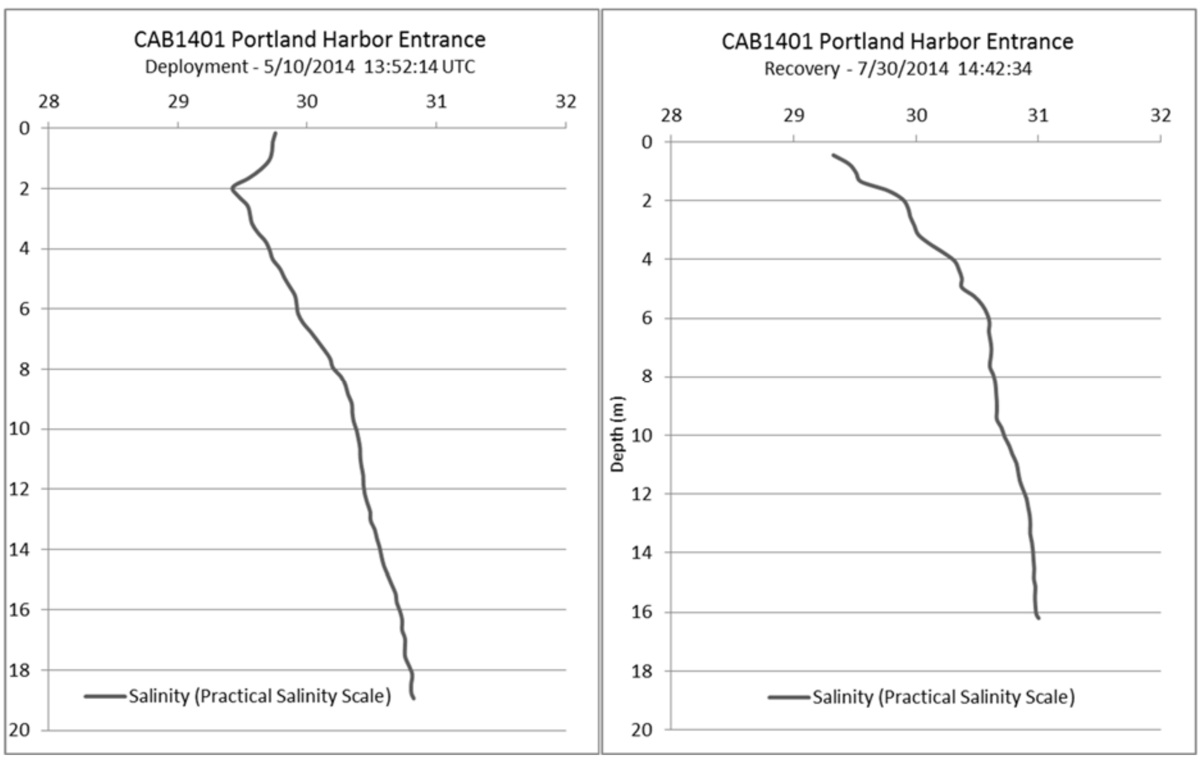

Figure 6. Salinity profiles for deployment and recovery at CAB1401.

5. DATA ACQUIRED

Data were acquired at 22 stations during the summer of 2014. Due to quality control issues, such as platform movement or instrument malfunctions, three of these stations did not have data for portions of the deployment period (these are separate from the three stations that did not have useable data and are indicated with an asterisk in Table 6. Table 6 lists data used in the analysis by station. Additionally, most stations have CTD data from casts taken at deployment and recovery.

Table 6. Data acquisition.

Station ID	Depth (m)	Total Bins	Bin Size (m)	Good Bins	Upper bin depth (ft.)	Begin Date	End Date	Data days
CAB1401	17.7	20	1.0	11	8.7	5/10/2014	7/30/2014	81
CAB1402	16.3	15	1.0	10	6.9	5/10/2014	6/16/2014	37
CAB1403*	18.3	25	1.0	11	6.3	5/10/2014	5/29/2014	19
CAB1404	14.7	20	1.0	11	7.3	6/17/2014	7/30/2014	43
CAB1405	7.1	30	0.5	12	2.5	6/17/2014	7/30/2014	43
CAB1406	11.8	25	1.0	9	3.4	6/18/2014	7/30/2014	42
CAB1407	13.0	20	1.0	7	5.0	5/10/2014	6/17/2014	38
CAB1409	16.0	25	1.0	11	3.9	6/19/2014	7/31/2014	42
CAB1410	32.0	20	2.0	10	10.8	6/19/2014	7/31/2014	42
CAB1411*	15.3	20	2.0	9	9.4	5/11/2014	5/23/2014	12
CAB1412	27.8	15	2.0	8	10.7	5/11/2014	6/17/2014	37
CAB1413	19.5	15	2.0	6	13.0	6/17/2014	7/31/2014	44
CAB1414	21.4	15	2.0	5	13.7	6/19/2014	7/31/2014	42
CAB1415	17.4	20	1.0	12	6.3	5/11/2014	6/17/2014	37
CAB1416	41.0	20	2.0	14	19.1	5/11/2014	6/17/2014	37
CAB1417	16.5	20	1.0	10	6.3	5/11/2014	6/17/2014	37
CAB1418	7.6	25	0.5	10	4.0	6/27/2014	8/1/2014	35
CAB1419	15.2	20	1.0	8	4.0	6/20/2014	8/2/2014	43
CAB1420	14.0	20	1.0	12	2.8	6/20/2014	8/1/2014	42
CAB1421*	15.5	25	1.0	12	3.5	6/20/2014	7/11/2014	21
CAB1423	10.7	15	1.0	9	2.6	5/17/2014	6/16/2014	30
CAB1425	9.9	30	0.5	11	1.4	5/12/2014	6/16/2014	35

***indicates not enough useable data were recovered**

6. STATION RESULTS

Significant stations of interest are briefly described qualitatively below. Stations that are judged to be significant are the newly established reference station for the region (Portland Harbor Entrance) and those which exhibit interesting dynamics. Harmonic analysis indicates the percentage of total energy that is due to tidal forcing.

The estimated station depth of the current meter is given in meters relative to an approximation of mean lower low water (MLLW). Due to the deployment being at depth with no contact to the surface while deployed, depth measurements are made using the instrument's pressure sensor. The calculated depth is a best approximation.

A description of the mean maximum flood current (MFC) and mean maximum ebb current (MEC) is given for the deepest measured depth, a depth near the middle of the water column and a near-surface depth. Bin 1 refers to the deepest measurement; bin number increases as you approach the water surface. The principal flood direction is the predominant axis of flow. Directions are provided in degrees from true north. The variance along this axis is provided to give an indication of how confined the flow is along this axis.

Three significant stations (1401 – Figure 7, 1407 – Figure 13, and 1419 – Figure 19) are described in the following sections. Five figures follow each station showing:

1. a north versus. east velocity component scatter plot at the uppermost good bin.
2. a velocity time series at the uppermost good bin with two plots. In the upper plot, a comparison of observed (green dots) and predicted (red line); in the lower plot the residual flow (the difference between observed and predicted).
3. a vertical profile of the mean velocity along the major (red) and minor (blue) axis of the water column. This represents the approximate residual (nontidal) circulation throughout the water column. The surface level is estimated (shown as a blue wavy line).
4. a vertical profile plot showing the timing and speed of MFC throughout the water column.
5. a vertical profile plot showing the timing and speed of the MEC throughout the water column.

The data presented below are a small subset of the full analyses conducted on the data sets. All analyses and plots for the entire time series and depths can be viewed in detailed station reports available through C-MIST (current measurement interface for the study of tides), which can be accessed via a public login.

6.1 CAB1401, Portland Harbor Entrance

Figure 7. Google Earth image showing location of CAB1401, Portland Harbor Entrance, in purple. Stations from deployment set one are in red and set two are in green.

This station was deployed from 5/10/2014 to 7/30/2014 at 17.7 m (58 ft) in a TRBM and collected 11 1-m bins that met quality control criteria. Bins 2, 8 and 11 are published in the Tidal Current Tables, representing approximate depths of 11.8 m, 5.8 m, and 2.7 m (39 ft, 19 ft, and 9 ft) below MLLW, respectively. Information from Bin 11 serves as the reference station denoted in Table 1 of the Tidal Current Tables. Currents at this location are mostly rectilinear and semidiurnal.

Harmonic analysis solved for 91–96% of the total current energy. Mean MFC currents range from 0.5 knots (25.7 cm/s) near the bottom to 0.7 knots (36.0 cm/s) near the surface. Mean MEC currents range from 0.9 knots (46.3 cm/s) near the bottom to 1.1 knots (56.6 cm/s) near the surface. There is a permanent flow out of Casco Bay at this location at all depths of 0.1-0.15 knots (5.1–7.7 cm/s) which accounts for much of the difference between MFC and MEC speeds. While MEC speeds are consistent, MFC speeds are weaker than the historic station data based on 2 days of data from 1941, which listed MFC and MEC at 1.0 and 1.1 knots (51.4 and 56.5 cm/s). Timing of all phases except SBF are within 10 minutes (min) of the historic station. SBF is 30 min later based on the new data.

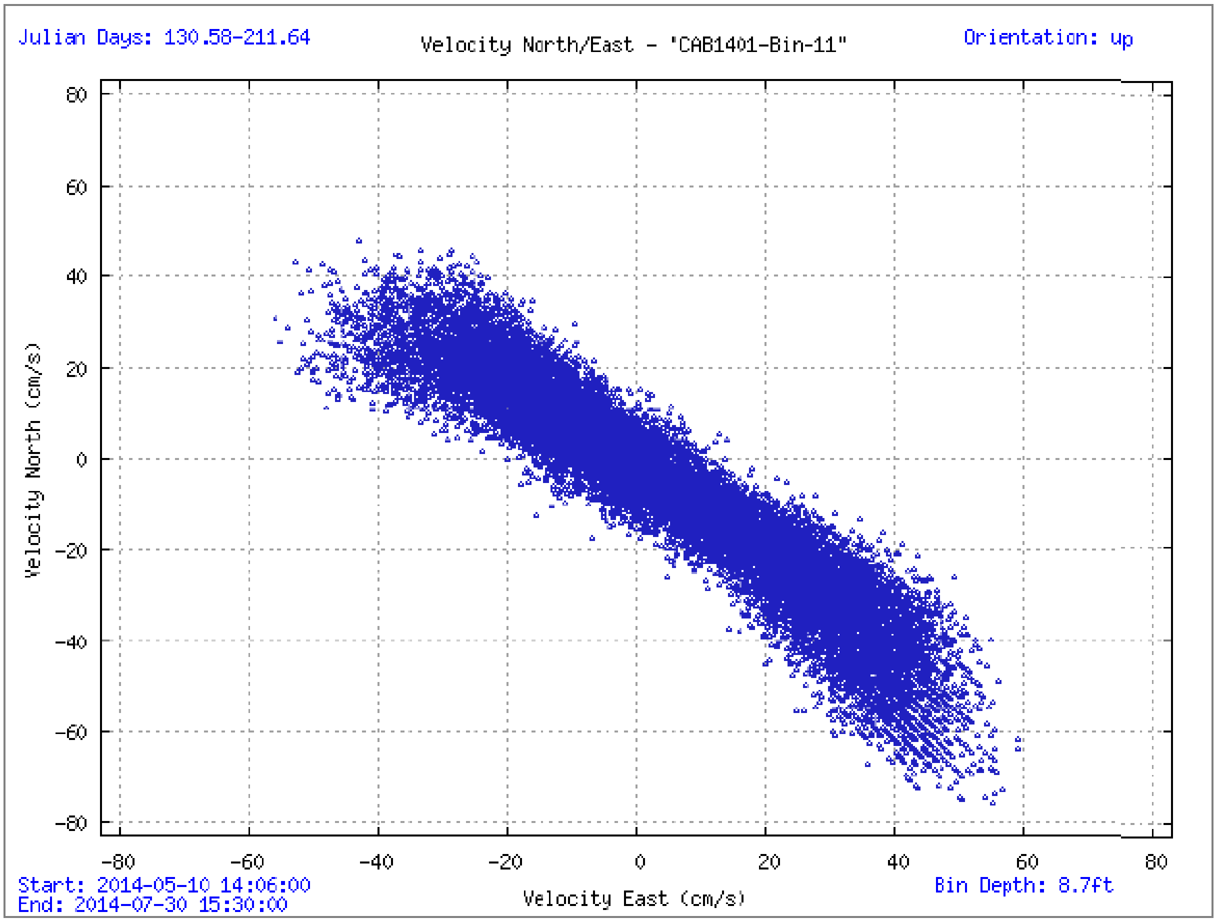

Figure 8. CAB1401 north versus east scatterplot, which shows the northern versus eastern components of the current at 2.64 m (8.66 ft) below MLLW.

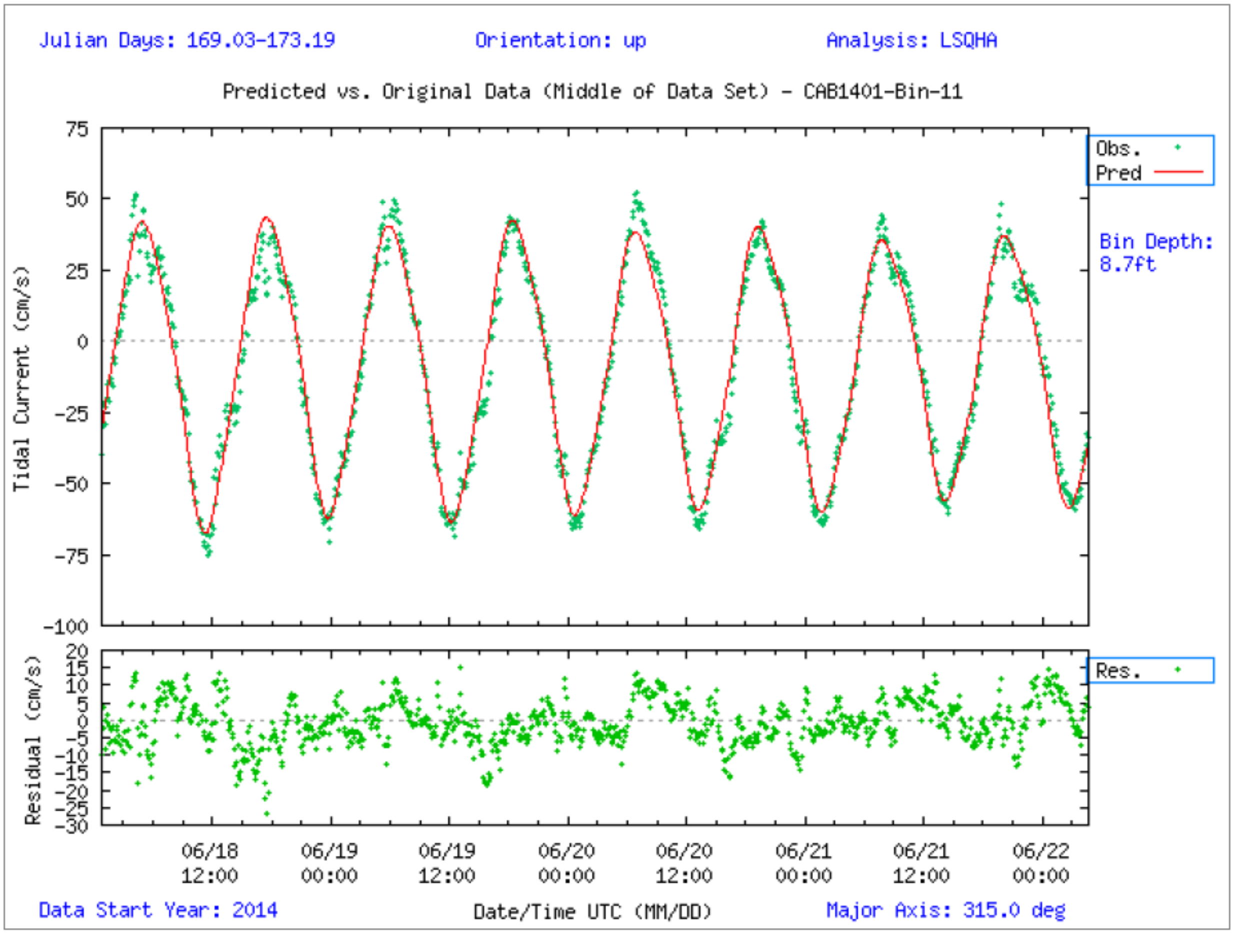

Figure 9. CAB1401 observed versus predicted currents, with residuals, at 2.64 m (8.66 ft) for the middle of the data set.

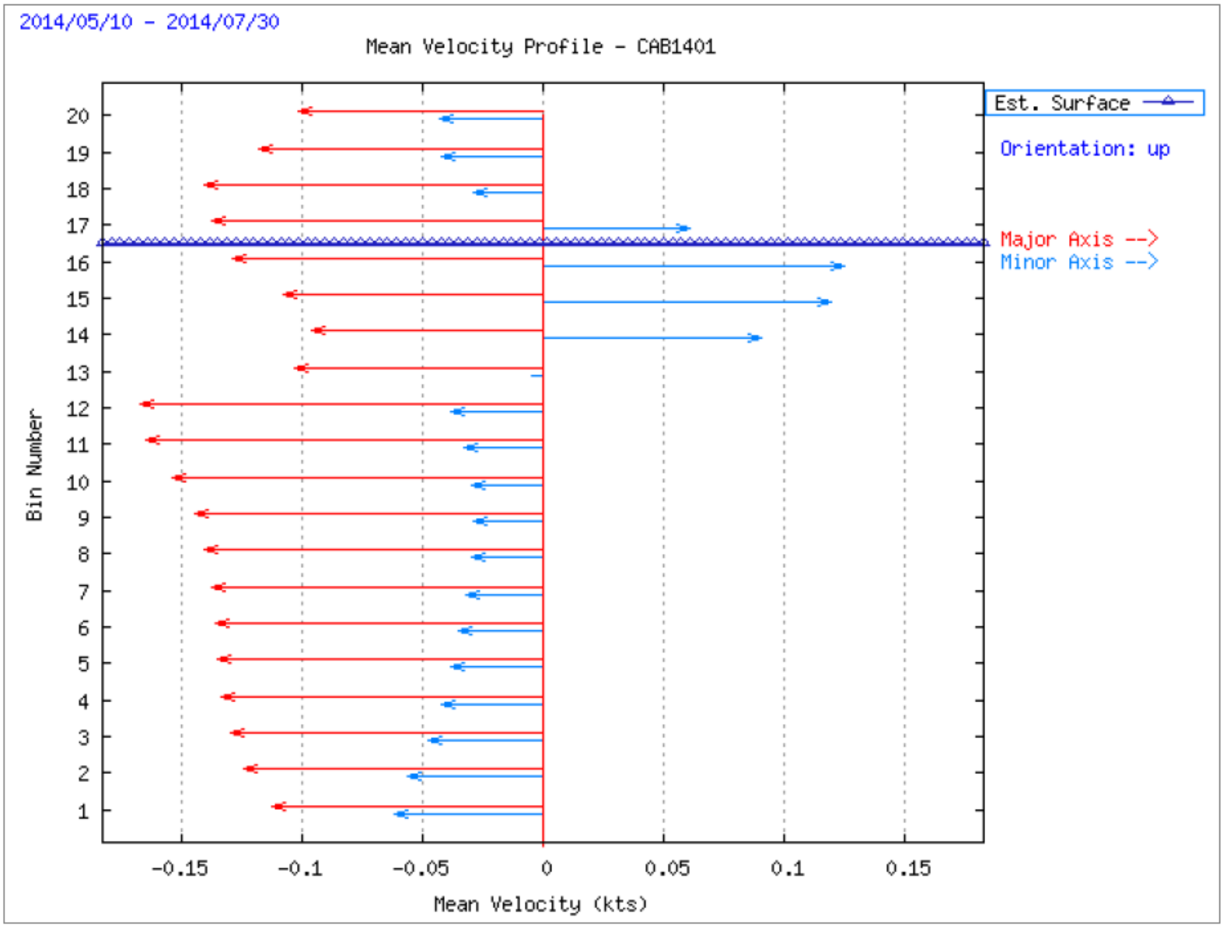

Figure 10. CAB1401 mean velocity profile by bin number. Bin 1 is approximately 12.64 m (41.47 ft) below MLLW and represents the deepest bin observed; bin spacing for this station was 1.00 m (3.28 ft). Although 20 bins are represented, bin 16 is the highest bin normally under water. The highest bin passing quality control criteria was determined to be bin 12.

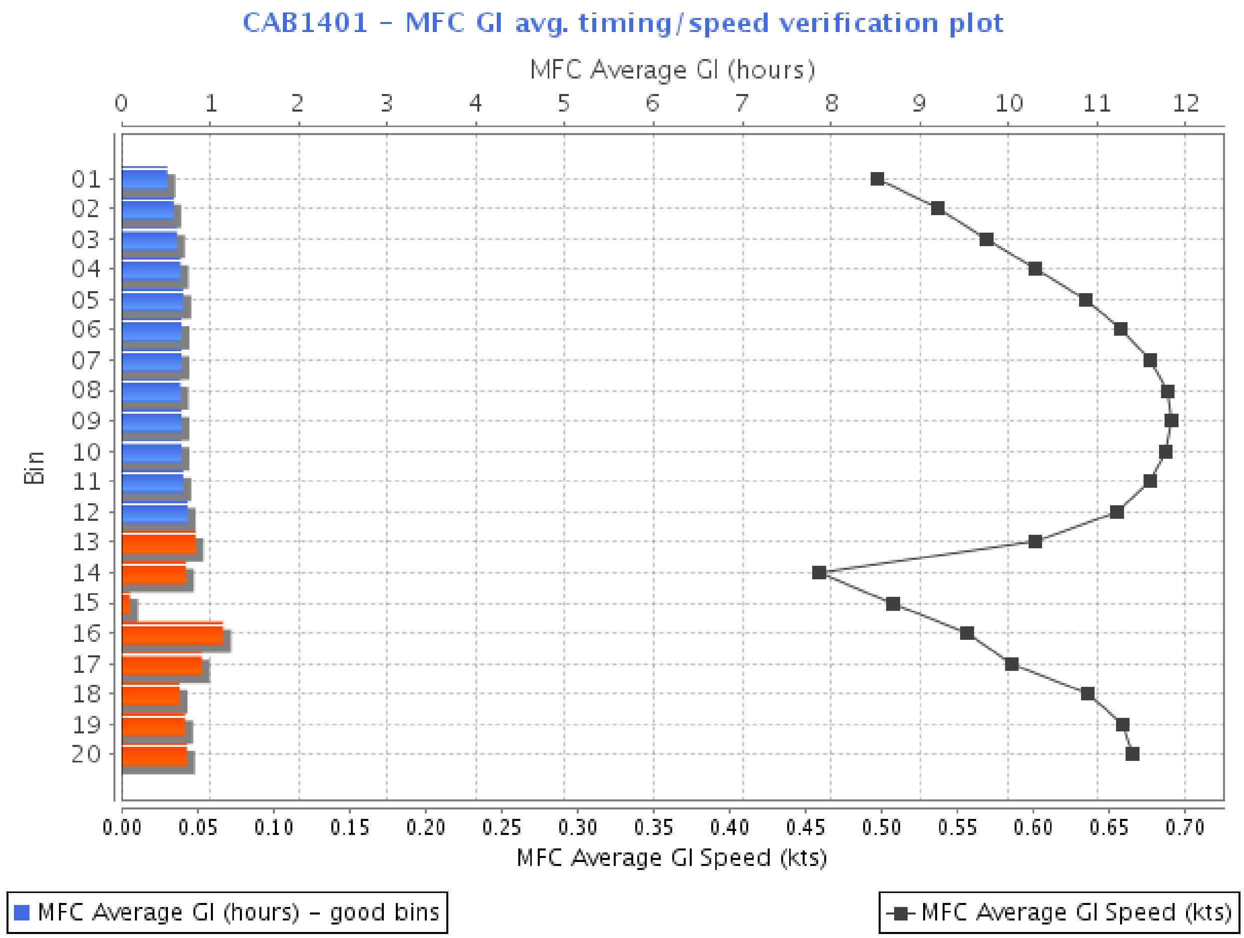

Figure 11. CAB1401 MFC timing (GI) and speed (in knots), by depth bin.

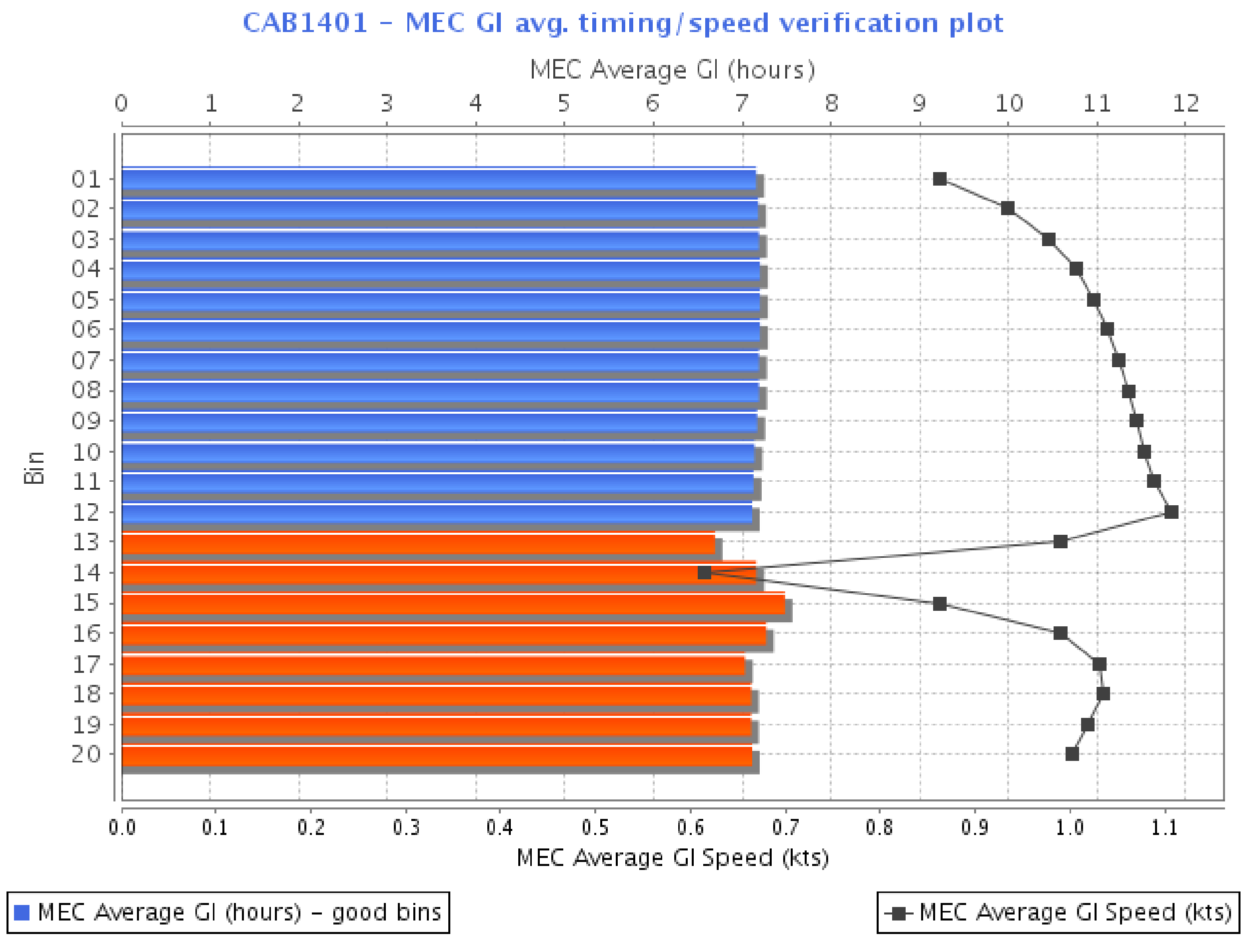

Figure 12. CAB1401 MEC timing (GI) and speed (in knots), by depth bin.

6.2 CAB1407, Fore River

Figure 13. Google Earth image of CAB1407, Fore River, Portland River Bridge.

This station was deployed from 5/10/2014 to 6/17/2014 at 13 m (43 ft) depth in an ES2 and collected 7 1-m bins which met quality control criteria. Bins are determined to be good if they pass checks to verify being below the water surface and quality control parameters.

This station is a subordinate station referenced off the Portland Harbor Entrance. Currents at this location are very rectilinear as they are directed by the river channel.

Harmonic analysis solved for 90–94% of the total current energy, indicating this location is predominately tidal. There are double ebb currents near the surface, most likely indicating a relatively high M_4 amplitude (compared with M_2). Mean MFC and MEC currents range between 0.4 and 0.5 knots (20.5–25.7 cm/s) at all depths. The standard deviation of MEC timing near the surface is a little over an hour due to the double ebbs.

This new station shows weaker currents than the historic station, which is based on 2 days of data from 1942. Timing of MFC, SBE, and MEC are about an hour earlier than the historic station based on this analysis. Timing of SBF is about half-hour earlier.

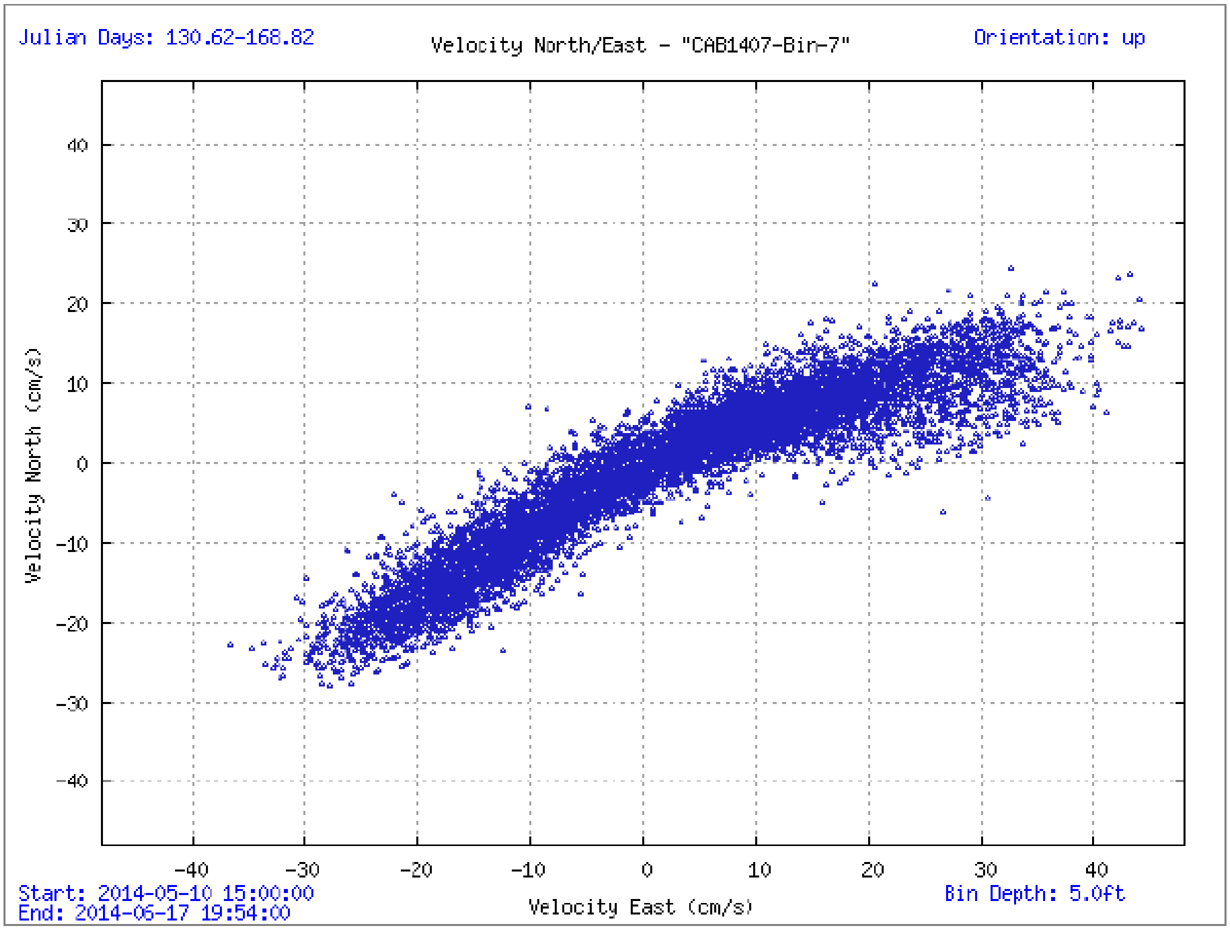

Figure 14. CAB1407 north versus east scatterplot, which shows the northern versus eastern components of the current at 1.53 m (5.02 ft) below MLLW.

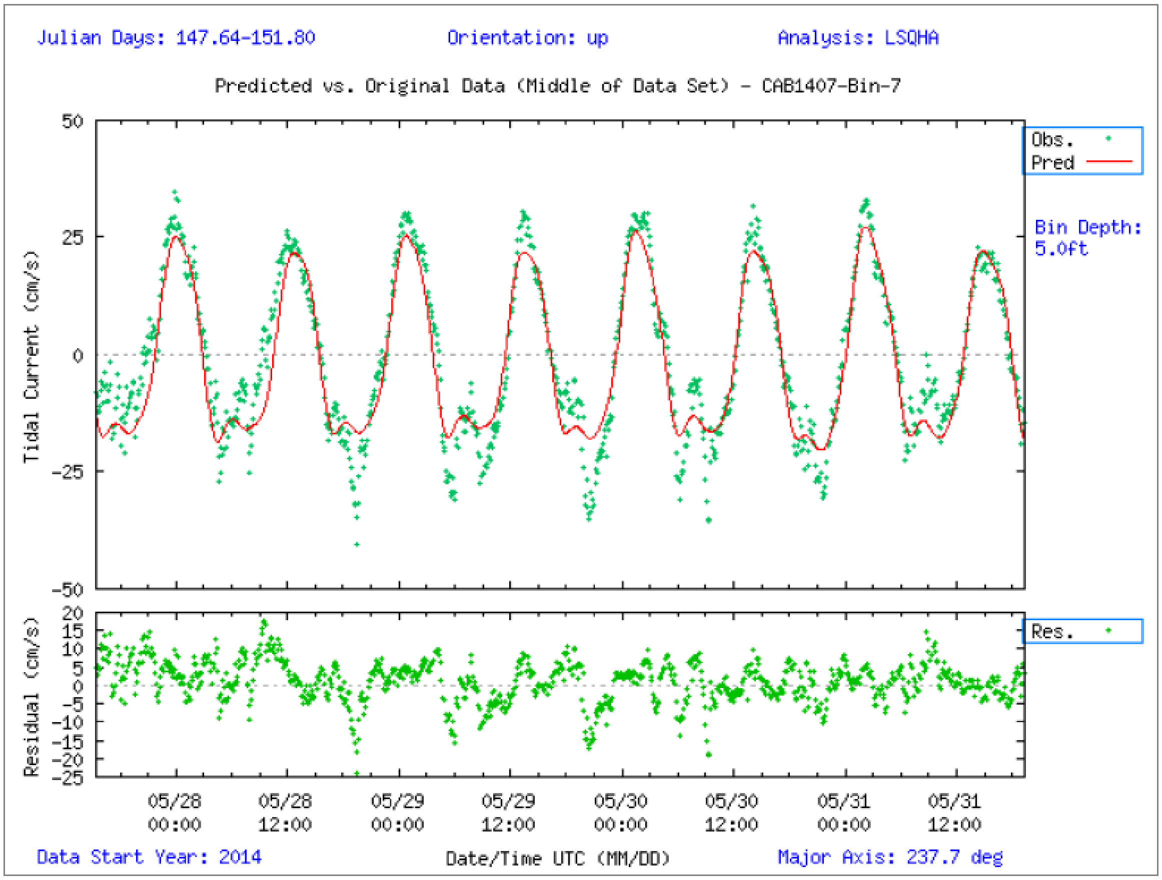

Figure 15. CAB1407 bin 7 observed versus predicted with residuals, at 1.53 m (5.02 ft) for the middle of the data set.

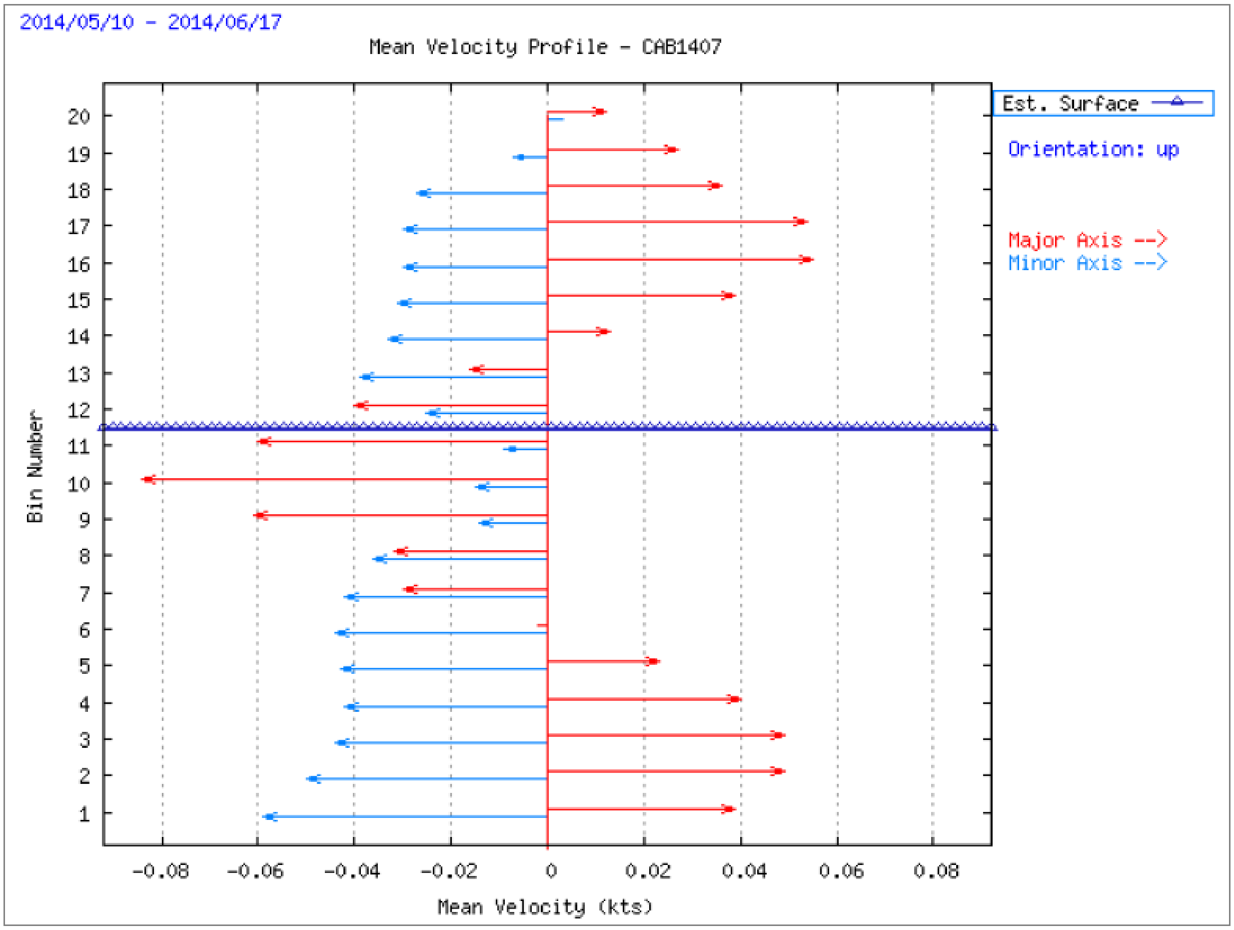

Figure 16. CAB1407 mean velocity profile by bin number. Bin 1 is approximately 24.70 m (81.04 ft) below MLLW and represents the deepest bin observed with bin spacing for this station was 1.00 m (3.28 ft). Although 20 bins are represented, bin 11 is the highest bin normally under water. The highest bin passing quality control criteria was determined to be bin 8.

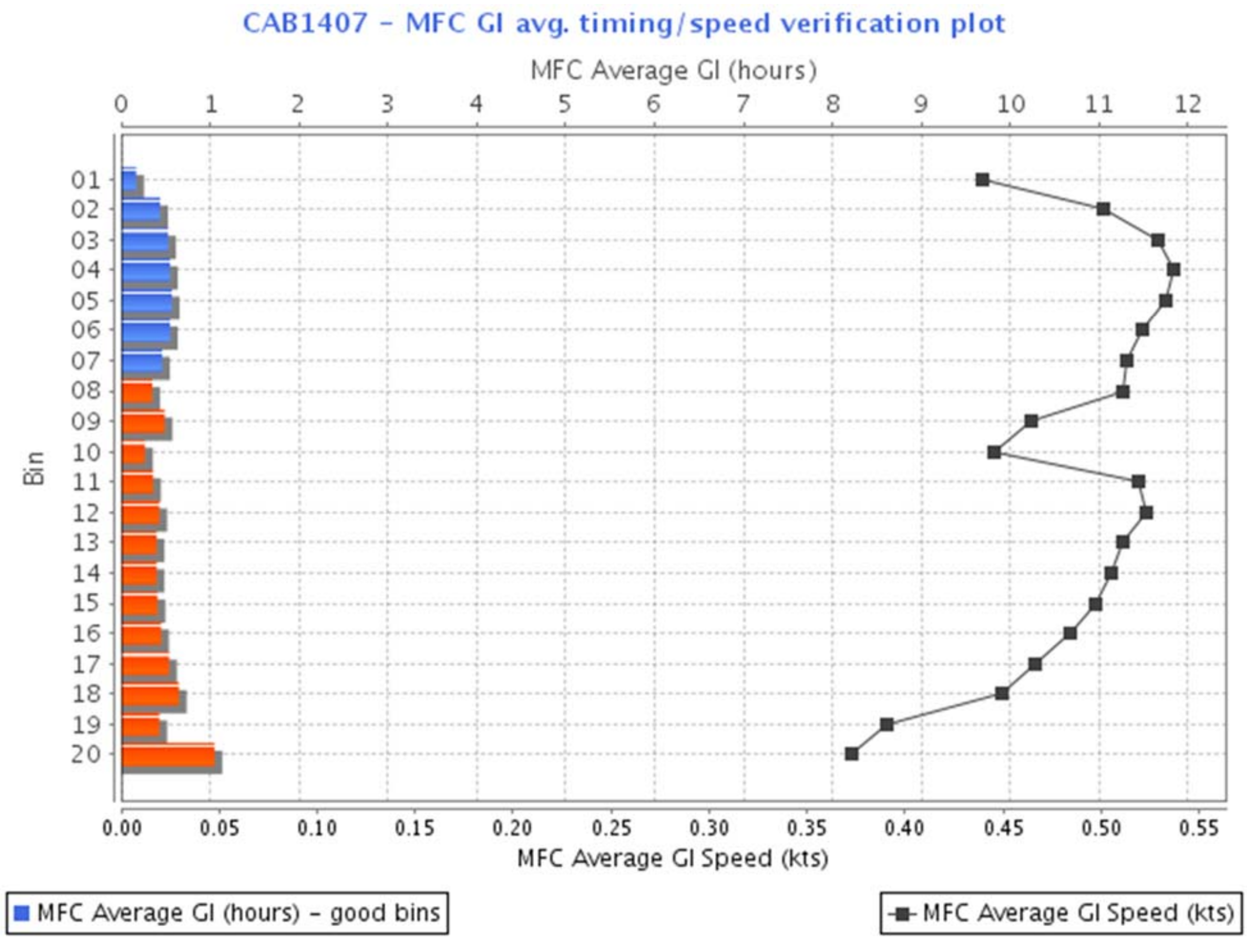

Figure 17. CAB1407 MFC timing (GI) and speed (in knots), by depth bin.

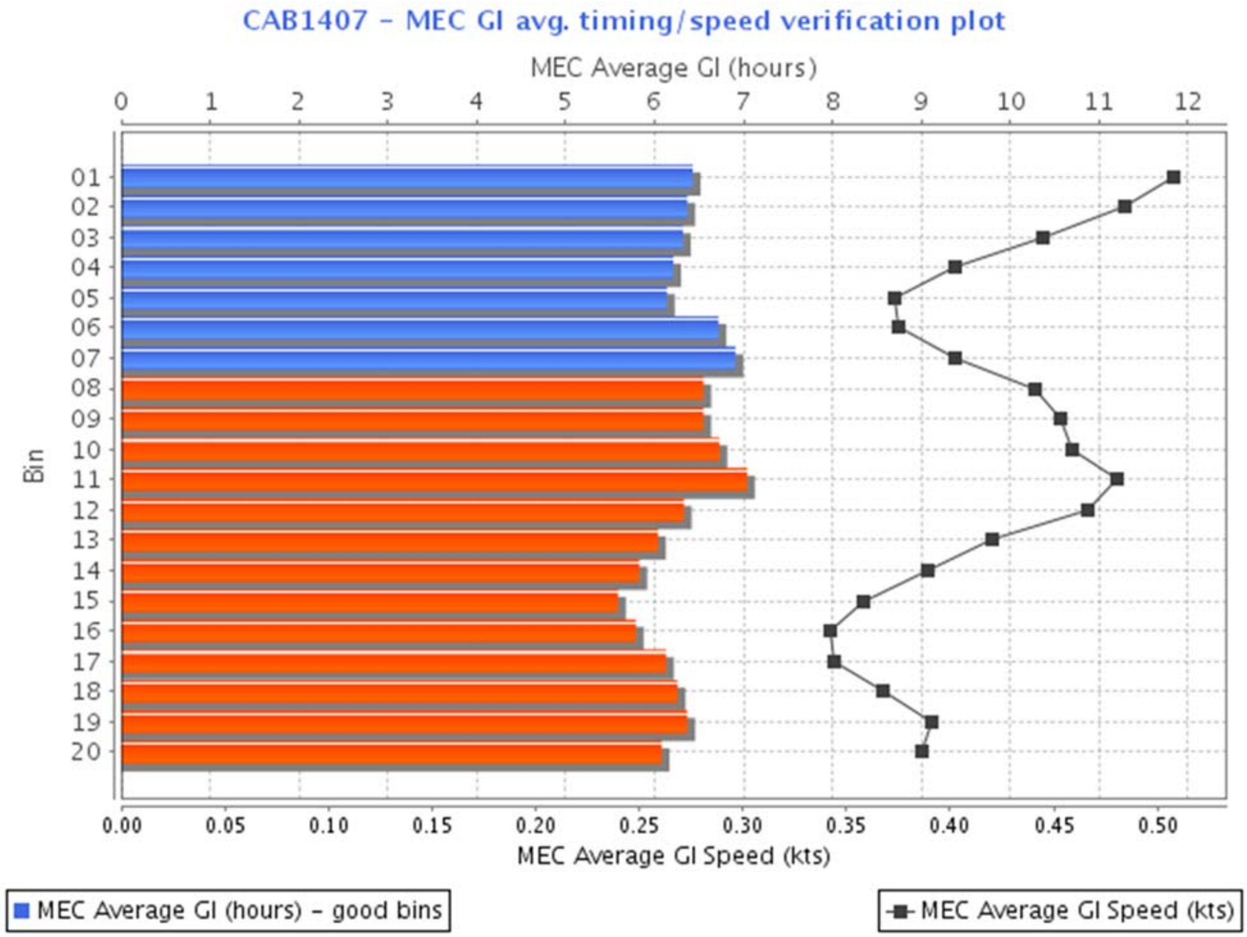

Figure 18. CAB1407 MEC timing (GI) and speed (in knots), by depth bin.

6.3 CAB1419, Goose Cove, south of Chops Passage, Kennebec River

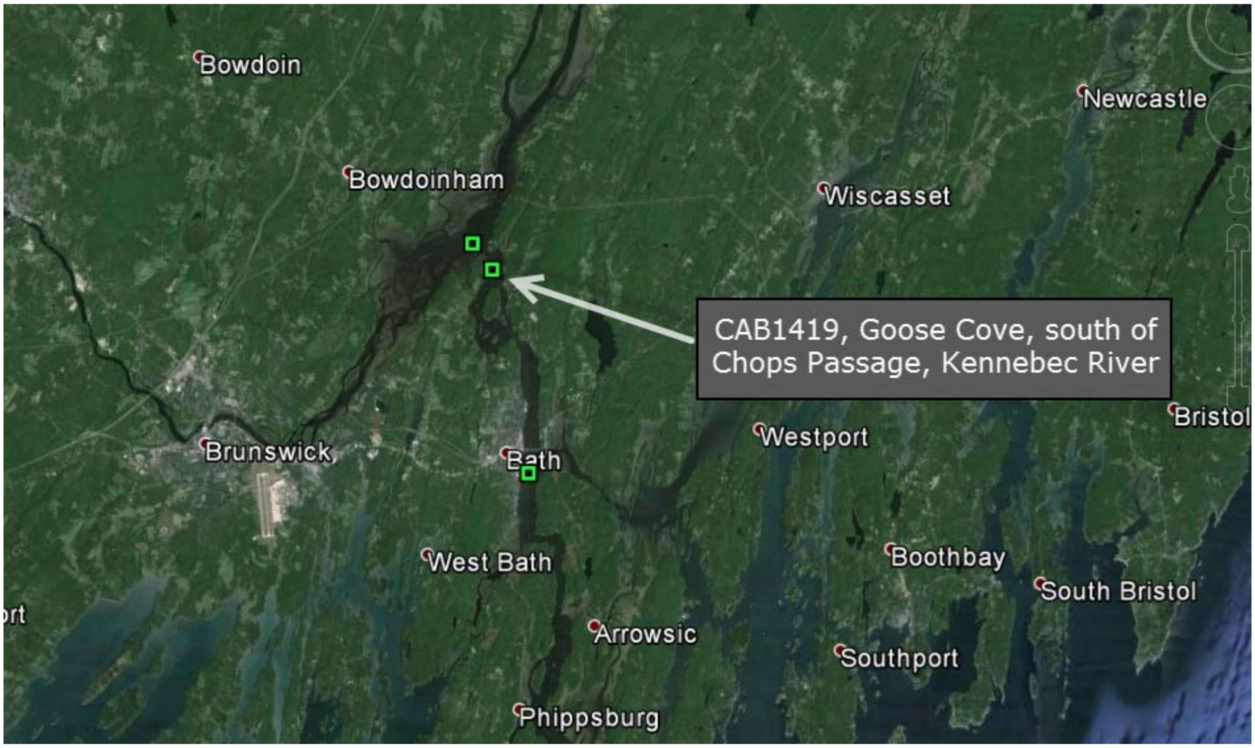

Figure 19. Google Earth image of CAB1419, Goose Cove, south of Chops Passage, Kennebec River.

This station was deployed from 6/20/2014 to 8/2/2014 at 15.2 m (50 ft) depth in a TRBM and collected 8 1-m bins, which met quality control criteria.

This station is a subordinate station referenced off the Portland Harbor Entrance. This station lies just south of the area referred to as The Chops Passage and is within Goose Cove. This is one of two stations, along with CAB1421 Merrymeeting Bay, north of the Chops, describing current movement through The Chops. This location is semidiurnal, and currents are very rectilinear and strong, with speeds near the surface exceeding 180 cm/s (3.5 knots) during peak ebbs, and 150 cm/s (2.9 knots) during peak floods.

Harmonic analysis solved for 98–99% of the total current energy. There is a permanent ebb flow of 0.4 knots at all depths due to the river runoff, making ebbs stronger than floods. Mean MFC currents range from 2.0 knots near the bottom to 2.4 knots near the surface. Mean MEC currents range from 2.6 knots near the bottom to 3.0 knots near the surface. The timing of all current phases is almost identical at all depths.

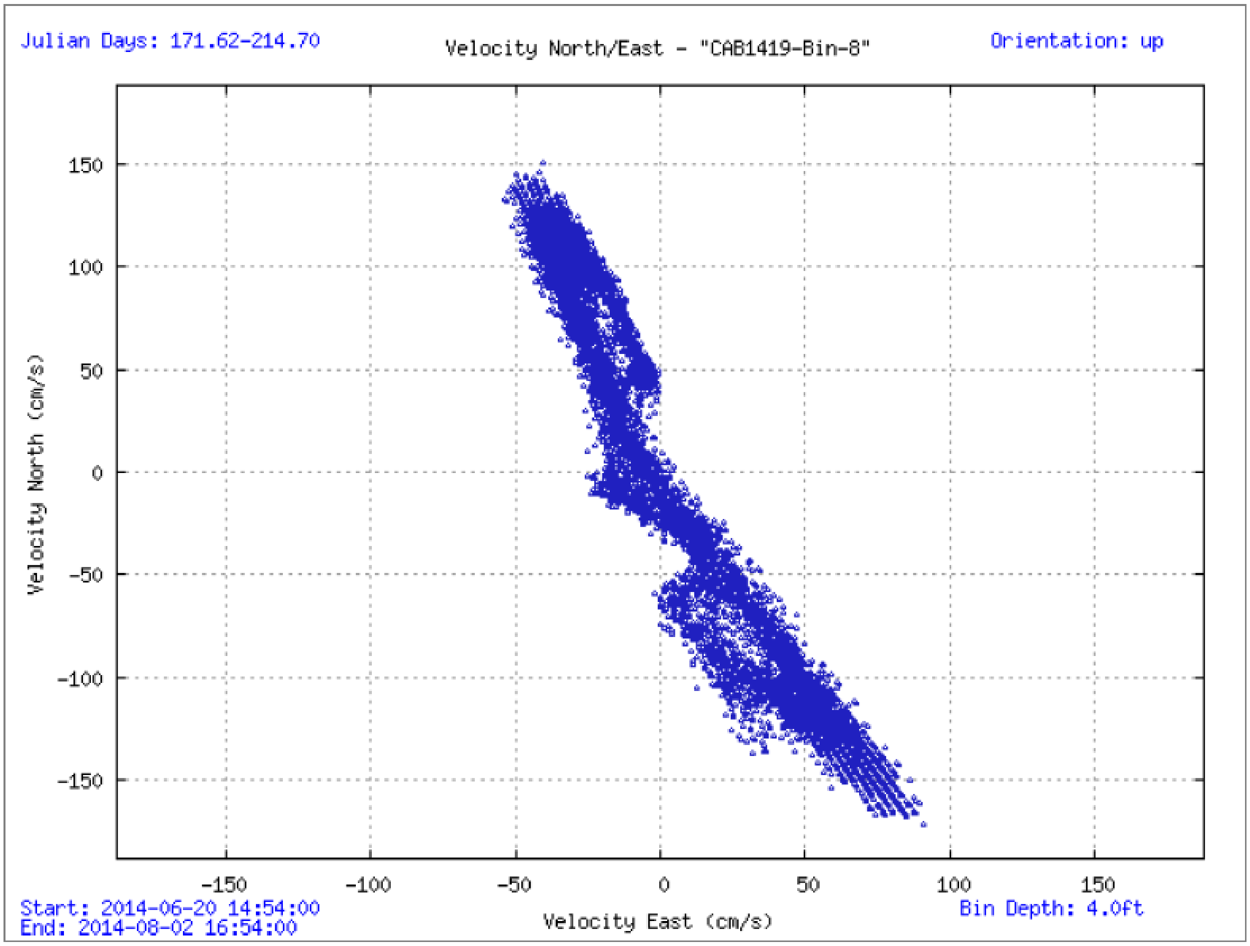

Figure 20. CAB1419 north versus east scatterplot, which shows the northern versus eastern components of the current at 1.23 m (4.04 ft) below MLLW.

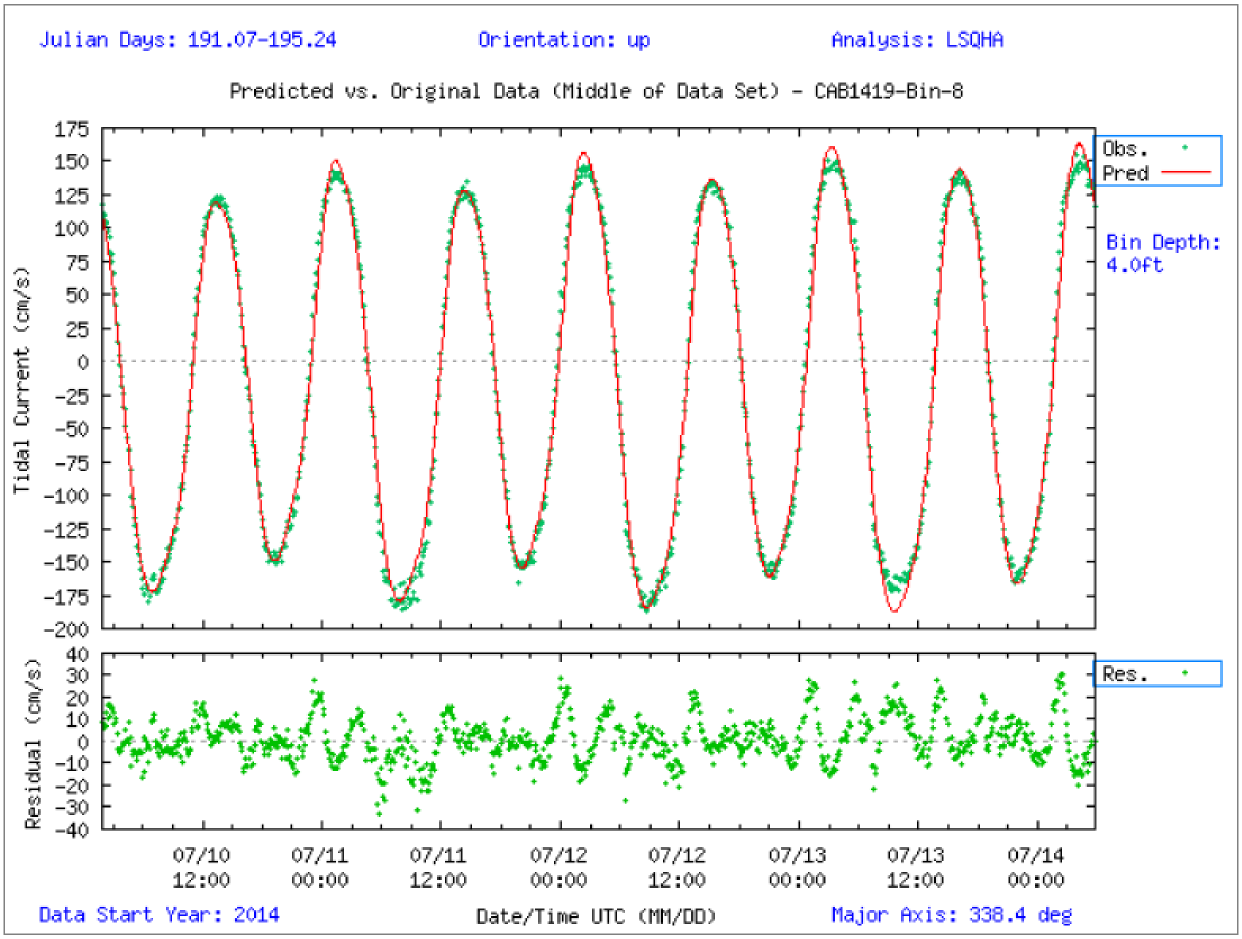

Figure 21. CAB1419 bin 8, observed versus predicted with residuals, at 1.23 m (4.04 ft) for the middle of the data set.

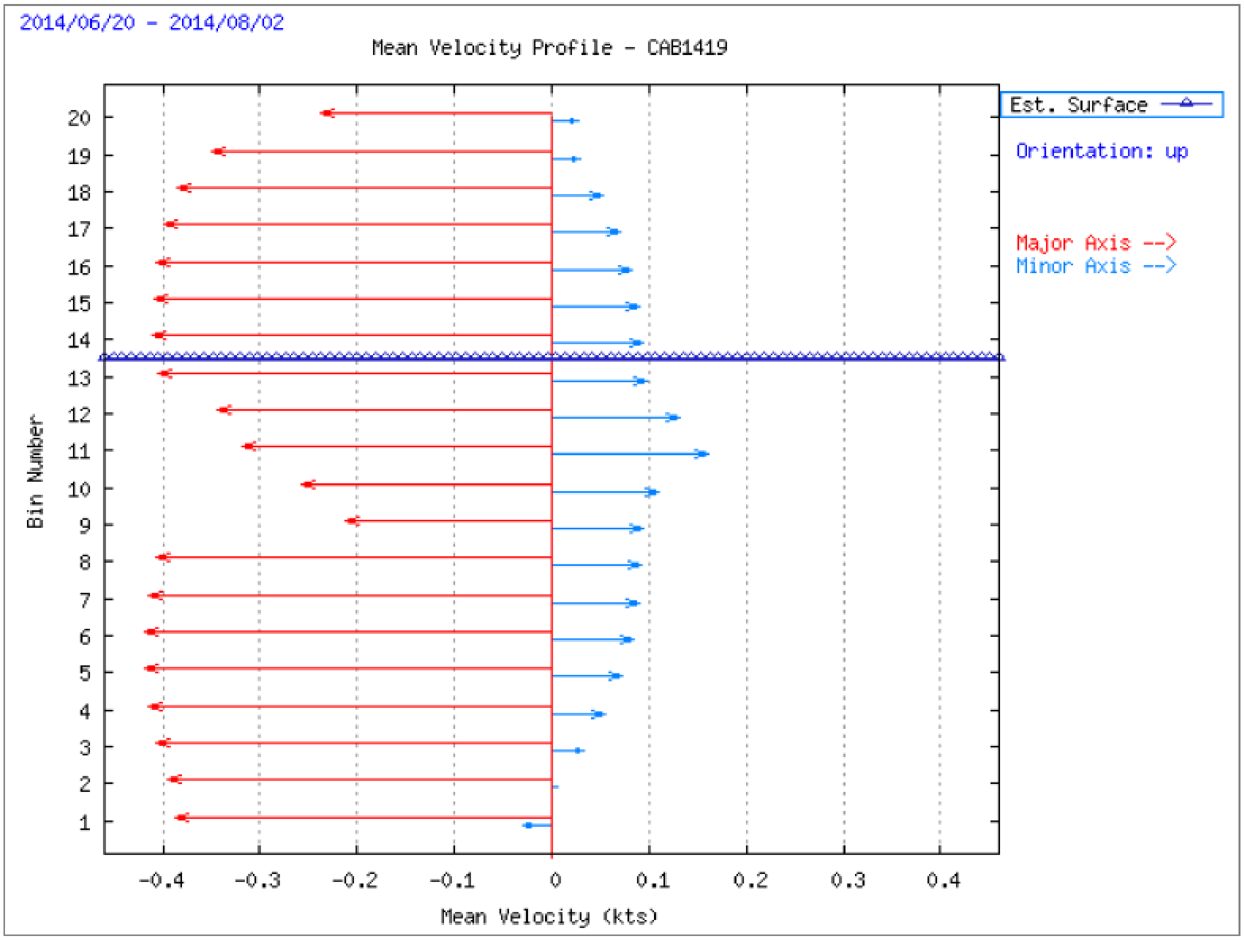

Figure 22. CAB1419 mean velocity profile by bin number. Bin 1 is approximately 8.23 m (27.00 ft) below MLLW and represents the deepest bin observed with bin spacing for this station of 1.00 m (3.28 ft). Although 20 bins are represented, bin 13 is the highest bin normally under water. The highest bin passing quality control criteria was determined to be bin 9.

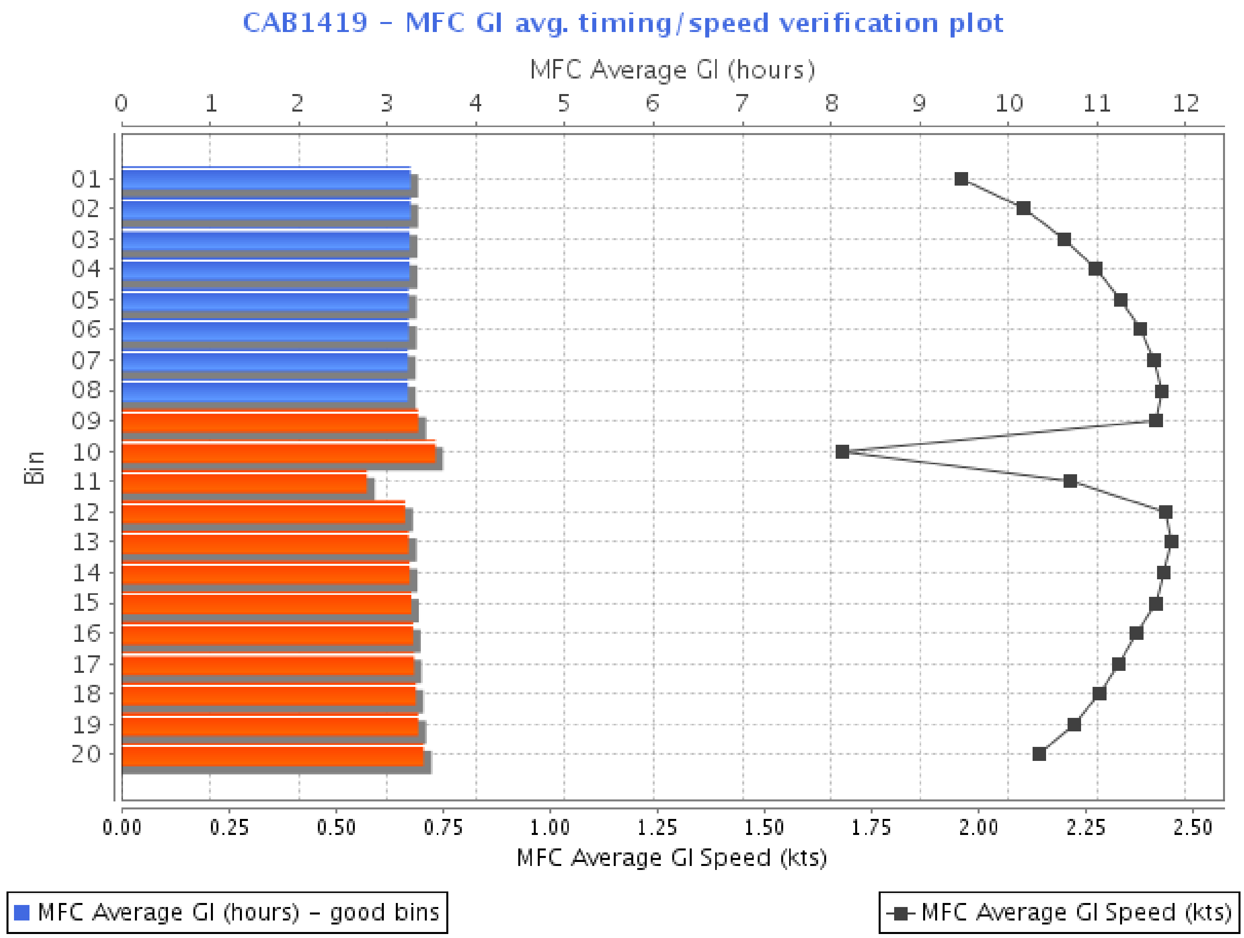

Figure 23. CAB1419 MFC timing (GI) and speed (in knots), by depth bin.

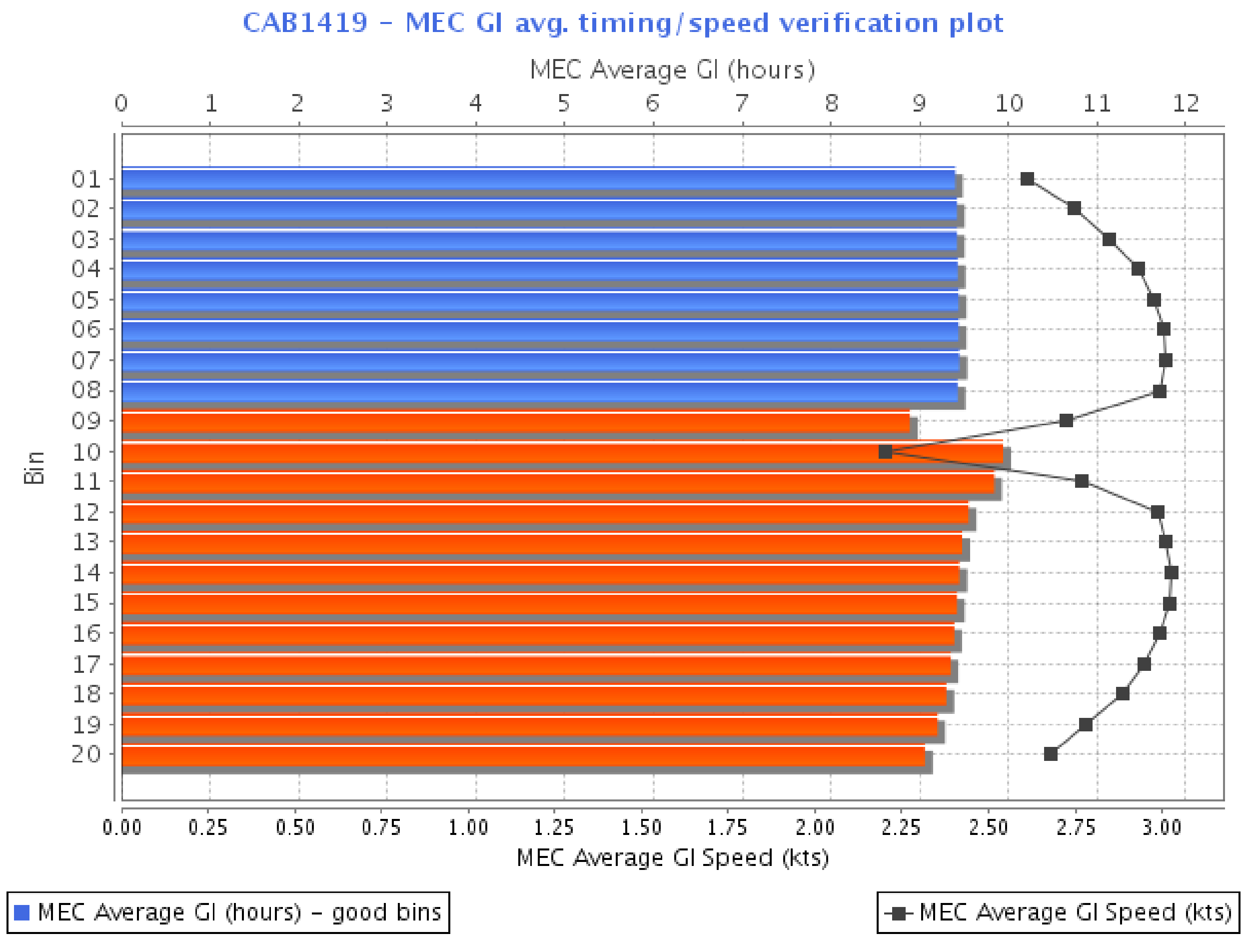

Figure 24. CAB1419 MEC timing (GI) and speed (in knots), by depth bin.

7. SPATIAL VARIATION

7.1 Harmonic Constituents

In general, tidal currents observed during this study were: 1) dominated by the M_2 tidal constituent, and 2) influenced by local bathymetric constrictions that limited flow to be predominantly oriented along the channel (major axis), creating extremely rectilinear flow fields.

The harmonic analysis for all stations generally solved for 25 harmonic constituents. Four of the most dominant constituents (M_2, S_2, O_1, and K_1) are mapped and provided in Table 7. In Casco Bay, the twice-daily pass of the moon, M_2 (the principal lunar semidiurnal constituent), is the most important factor influencing the flow within this basin.

On average, the observed amplitude of M_2 along the principal axis was about 9.8 times greater than S_2, which is the principal solar semidiurnal constituent and the next strongest constituent. The amplitude of M_2 was 11.4 times greater than O_1 and 19.6 times greater than K_1 along the principal axis. An anomaly was observed at station CAB1423, which showed a major axis amplitude for K_1 1.6 times that of M_2. This station is in a cove open to the ocean, and the anomaly is likely influenced by the local bathymetry.

Table 7. Major contituent amplitudes and phases

Station ID	M_2 amplitude	M_2 phase	S_2 amplitude	S_2 phase	O_1 amplitude	O_1 phase	K_1 amplitude	K_1 phase
CAB1401	0.821	244.7	0.106	270.3	0.050	48.5	0.048	18.1
CAB1402	0.784	227.6	0.101	241.4	0.074	12.2	0.011	55.8
CAB1403	0.316	197.1	0.02	227.0	0.019	322.1	0.009	64.6
CAB1404	0.541	225.1	0.058	273.3	0.039	85.8	0.025	90.8
CAB1405	0.186	247.6	0.042	276.9	0.025	171.1	0.025	195.0
CAB1406	0.456	244.3	0.075	263.5	0.025	35.8	0.025	16.7
CAB1407	0.447	237.8	0.011	294.4	0.027	102.1	0.026	115.4
CAB1409	0.659	217.4	0.079	229.7	0.041	60.9	0.024	86.3
CAB1410	0.994	240.8	0.131	252.4	0.066	58.6	0.027	344.6
CAB1411	0.166	241.3	0.008	211.1	0.009	169.7	0.059	17.6
CAB1412	0.851	235.7	0.177	298.0	0.108	42.9	0.062	24.2
CAB1413	0.48	218.9	0.081	216.3	0.061	10.0	0.026	16.3
CAB1414	0.409	275.0	0.077	324.9	0.074	103.2	0.056	36.7
CAB1415	0.598	245.9	0.072	263.6	0.065	53.7	0.032	34.5
CAB1416	0.971	230.3	0.12	263.4	0.071	24.4	0.040	14.2
CAB1417	0.239	215.6	0.038	232.5	0.076	332.9	0.015	265.6
CAB1418	1.344	336.5	0.149	10.0	0.102	112.4	0.065	120.3
CAB1419	2.701	312.6	0.312	349.3	0.198	92.5	0.184	86.3
CAB1420	2.104	298.7	0.237	323.3	0.161	85.1	0.123	85.1
CAB1421	1.394	316.0	0.133	353.1	0.144	121.9	0.097	137.1
CAB1423	0.121	297.3	0.019	290.8	0.198	42.6	0.019	134.9
CAB1425	0.339	259.0	0.069	311.1	0.069	60.7	0.054	38.4

The four principal tidal constituents can be represented by an elliptical path, traced around each station. Representative ellipses relate an average magnitude and direction of the major and minor axes of flow. In the open ocean, a tidal ellipse is nearly circular, as there are no significant bathymetry changes to alter the flow. However, as Casco Bay is marked by numerous islands, inlets, and passages, the motion possible along the minor axis of flow is constricted, to the point where it is almost negligible in most locations. In many cases, the resulting elliptical path is largely rectilinear along the principal axis of flow, which is usually the river channel. These constrictions are best represented in the Kennebec River stations, as seen in the right pane on Figure 25. The relative speed of constituents M_2, S_2, O_1, and K_1, in Figure 25–28 have been adjusted in scale to better visualize the ellipses.

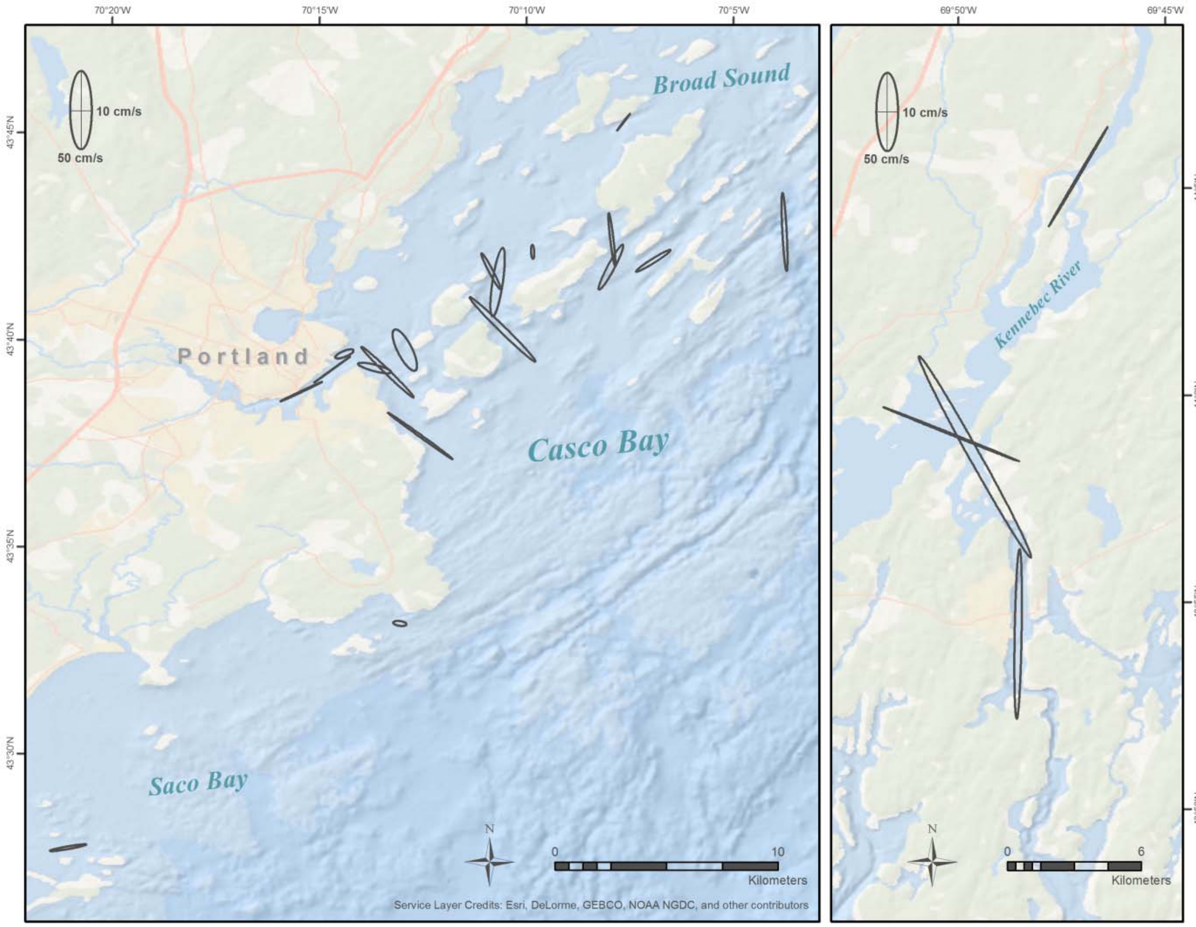

Figure 25. Map of near surface M_2 tidal constituent ellipses. M_2 - Principal lunar semidiurnal constituent (speed: 28.984 degrees per mean solar hour).

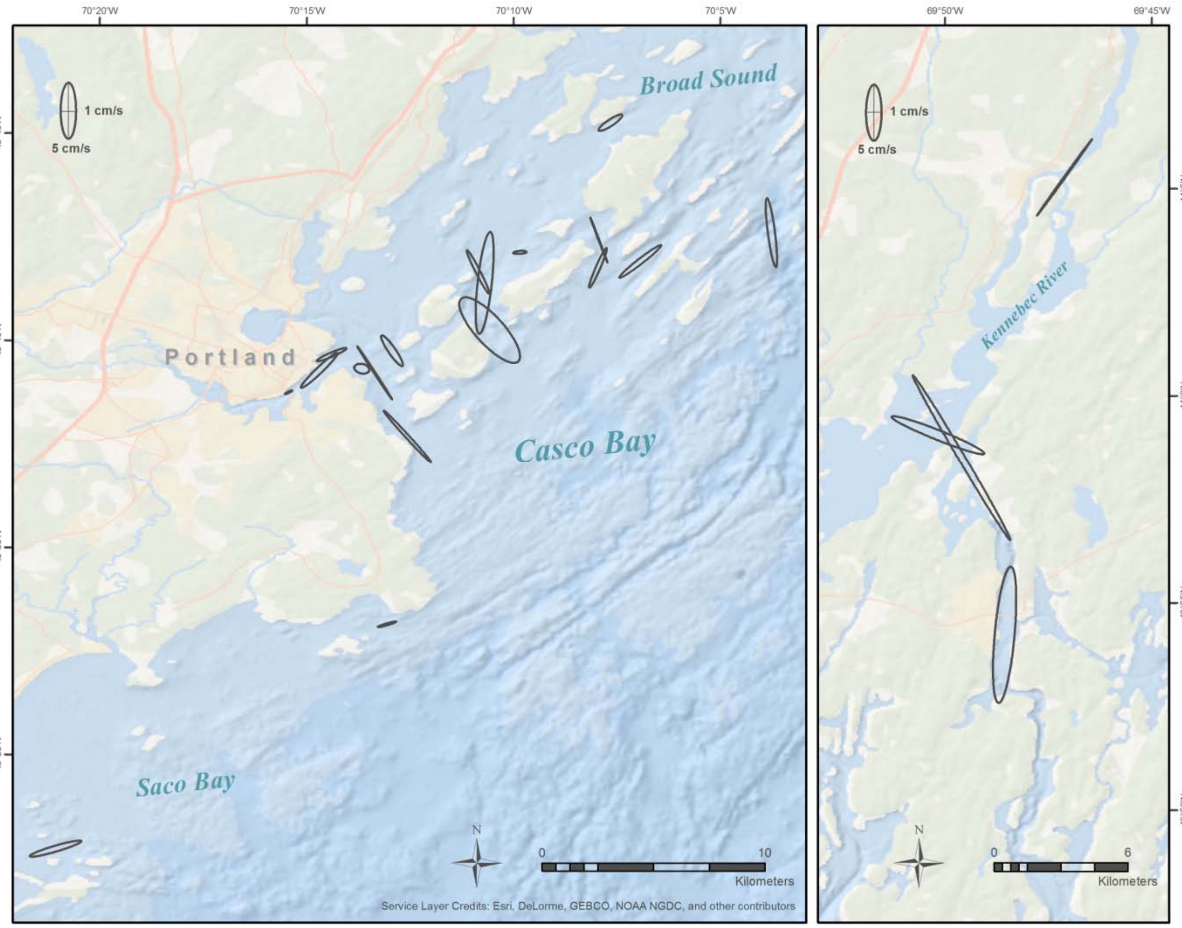

Figure 26. Map of near surface S_2 tidal constituent ellipses. S_2 – Principal solar semidiurnal constituent (speed: 30.000 degrees per mean solar hour).

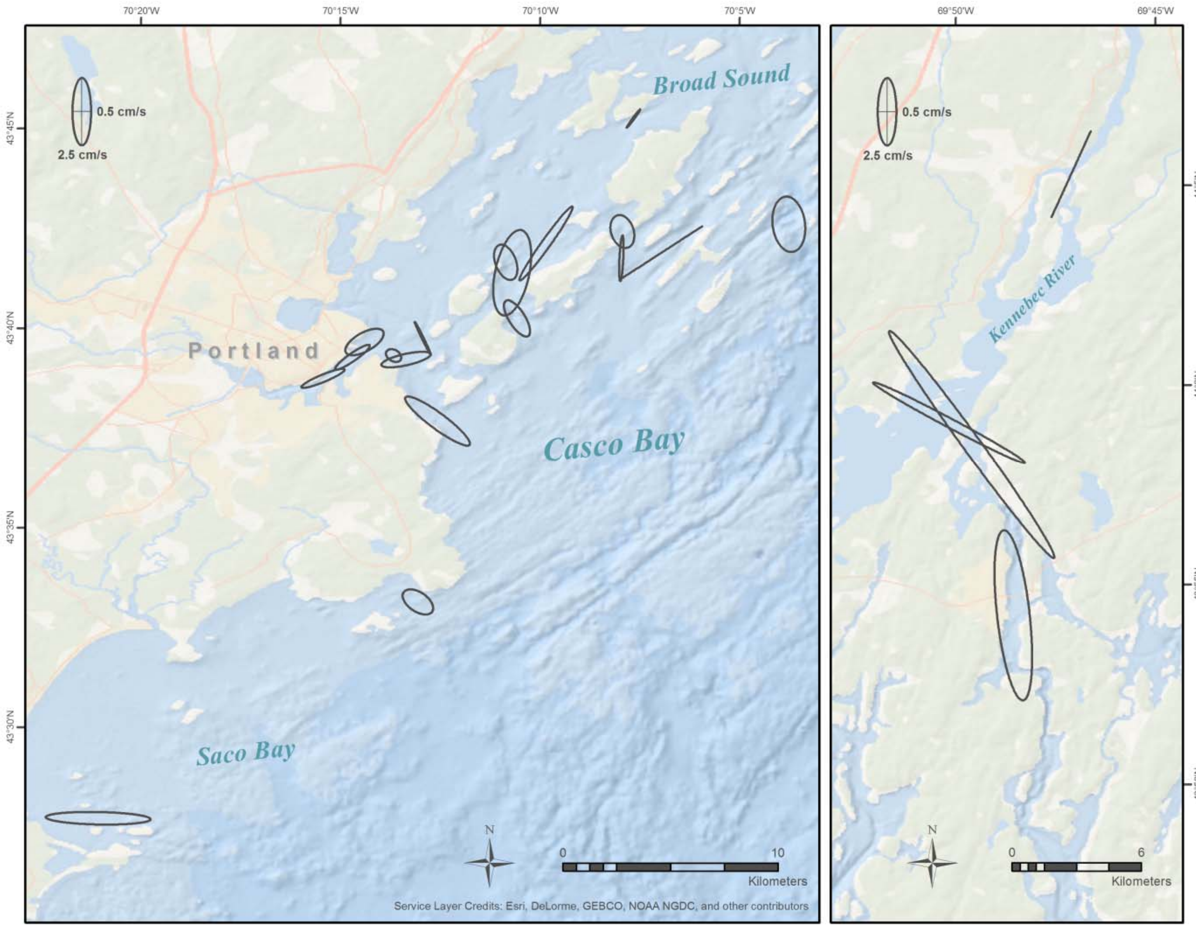

Figure 27. Map of near surface O_1 tidal constituent ellipses. O_1 - Lunar declinational diurnal constituent (speed: 13.943 degrees per mean solar hour).

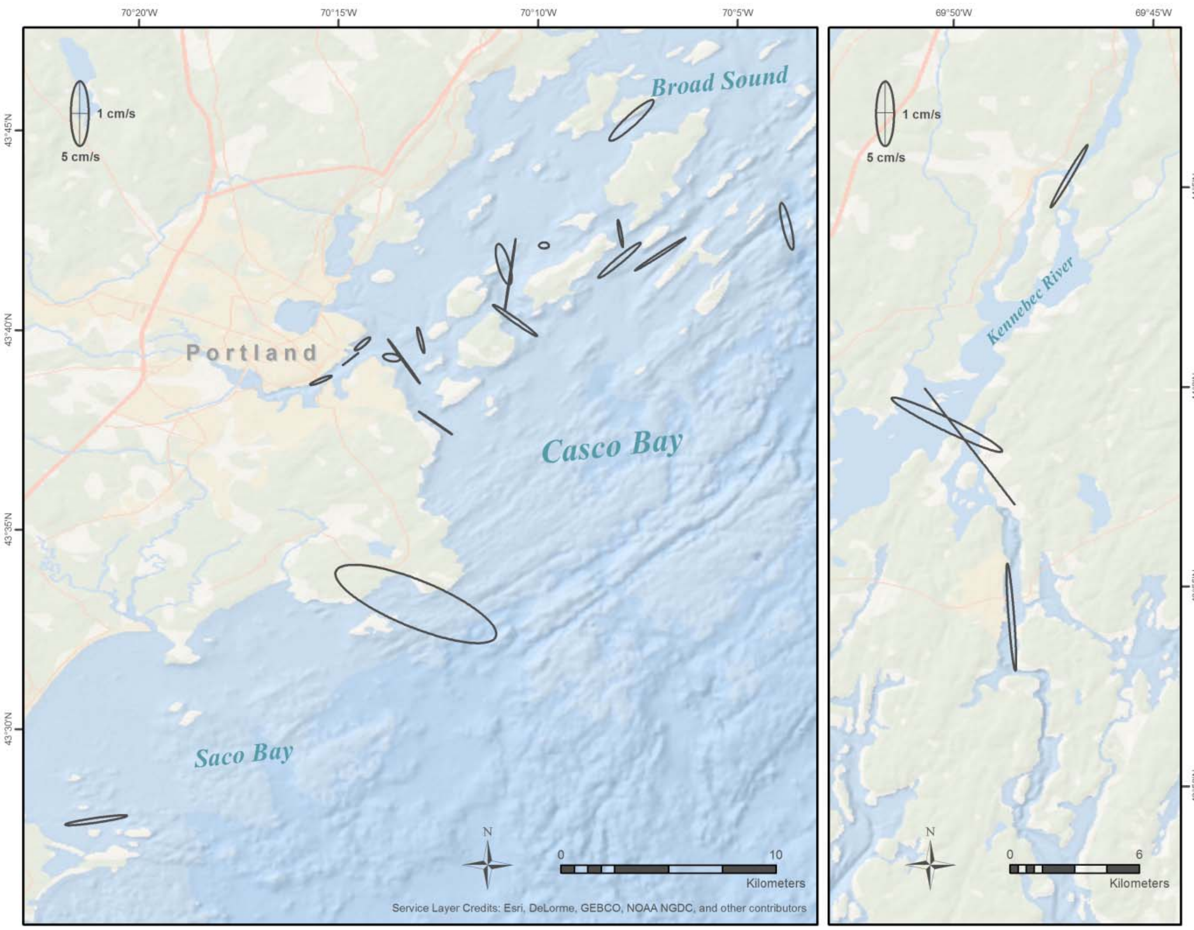

Figure 28. Map of near surface K_1 tidal constituent ellipses. K_1 - Lunisolar declinational diurnal constituent (speed: 15.041 degrees per mean solar hour).

7.2 Near-Surface Phases of the Tide (Timing and Speed)

The following maps (Figure 29–31) show the spatial distribution of the speeds at each station during the maximum flood and ebb currents. Speeds are highest in the Kennebec River and generally weakest in locations that are not constricted by bathymetry.

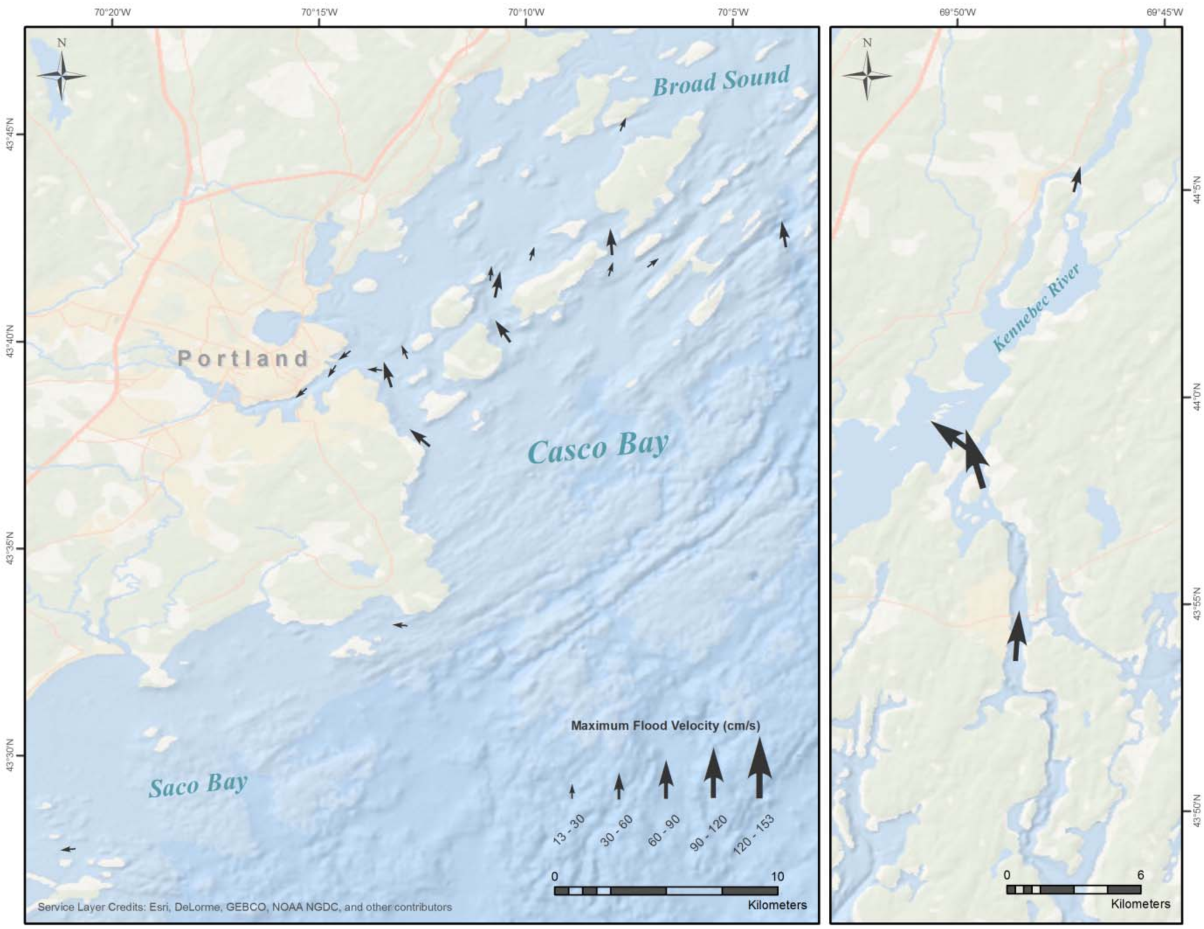

Figure 29. Map of the near surface average MFC speed.

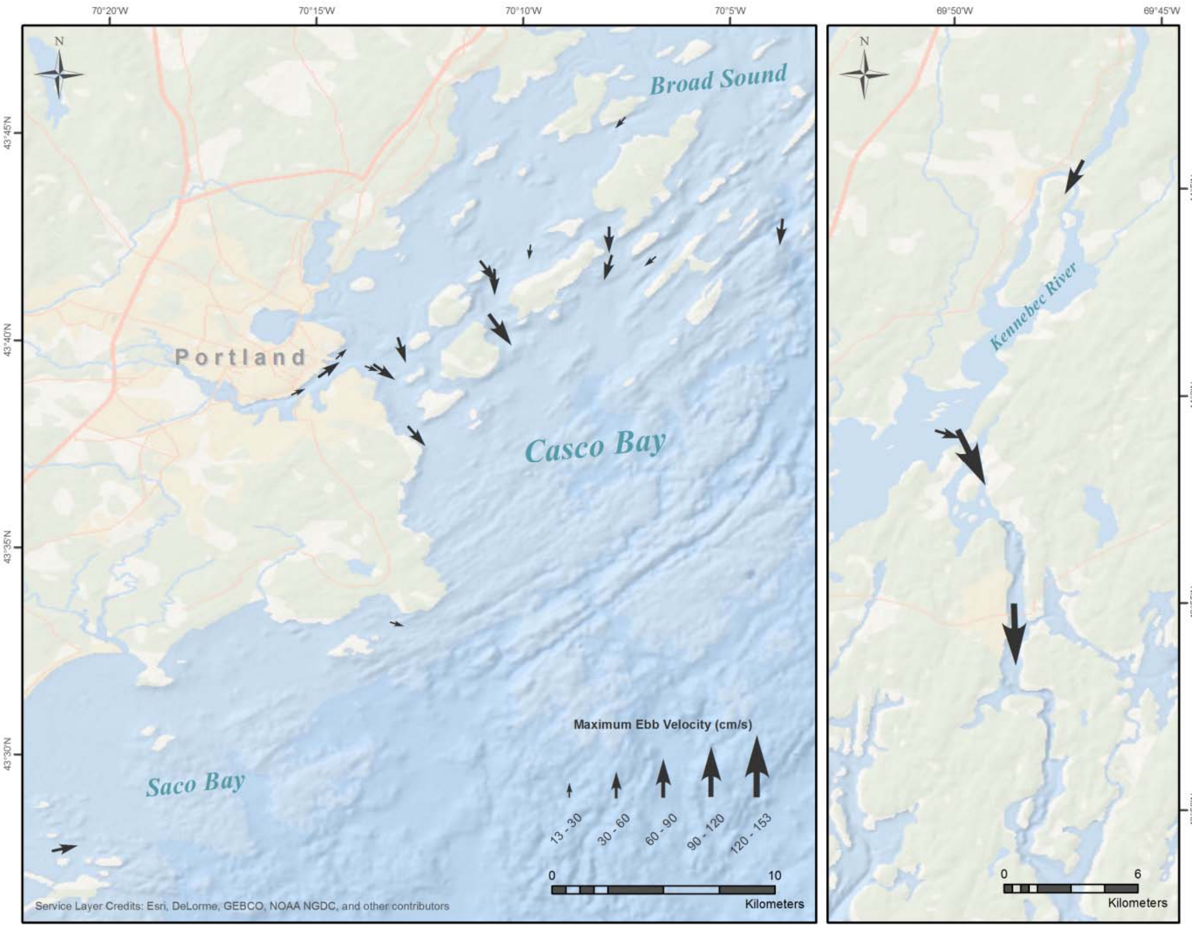

Figure 30. Map of the near surface average maximum ebb current (MEC) speed.

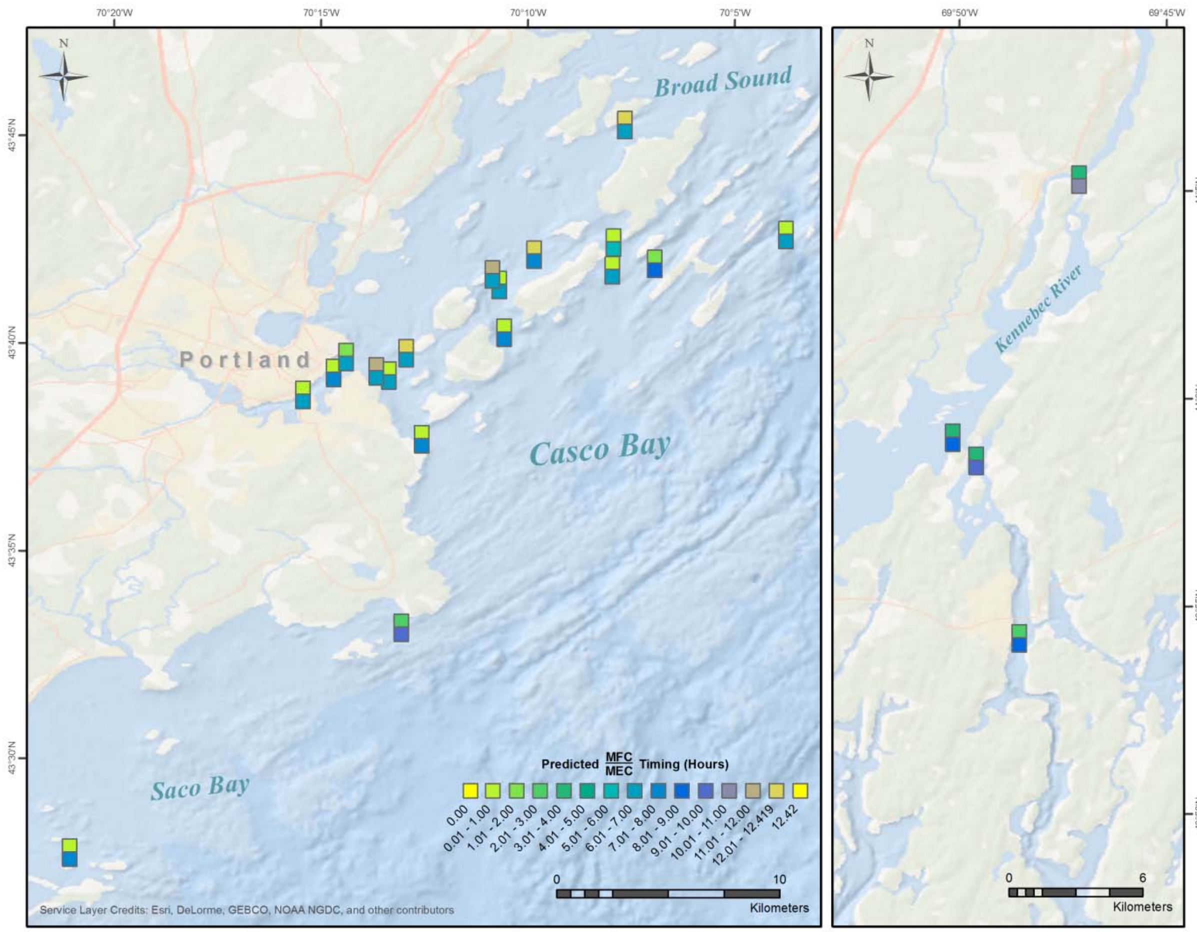

Figure 31. Map of the timing (GI) of near surface MFC (top) and MEC (bottom).

8. SUMMARY

Data were successfully collected from mid-May through July 2014 at 22 stations throughout the Casco Bay region of Maine, culminating in a comprehensive two-month data set of currents, water temperature, and pressure observations. These raw data are readily available and were used to update the Tidal Current Tables and validate a hydrodynamic model (GoMOFS). The raw data are available on the CO-OPS website. This data set is available to further investigate the circulation of Casco Bay and vicinity.

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ACRONYMS

ADCP	acoustic Doppler current profiler
cm	centimeter
CO-OPS	Center for Operational Oceanographic Products and Services
CTD	conductivity, temperature, and depth
CAB	Casco Bay
ft	feet
GoMOFS	Gulf of Maine Operational Forecast System
GI	Greenwich Interval
GT	great diurnal tide
IHO	International Hydrographic Organization
kHz	kilohertz
m	meter
M	nautical mile
MEC	maximum ebb current
MFC	maximum flood current
MHHW	mean higher high water
MLLW	mean lower low water
MN	mean tide range
MTRBM	miniature trawl-resistant bottom mount
NCOP	National Current Observation Program
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
R/V	Research Vessel
s	second
SBE	Slack before ebb
SBF	slack before flood
SUBS	Streamlined Underwater Buoyancy System
TRBM	trawl-resistant bottom mount
TRDI	Teledyne RD Instruments